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Independent Study

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The goal of any assistive listening device is to provide improved auditory perception. This study examined specific auditory features perceived by profoundly hearing impaired children using two different devices -- conventional binaural hearing aids and the Nucleus 22 Channel Cochlear Implant. These devices differ significantly in their functioning, as hearing aids are designed to amplify all sounds in the environment and the cochlear implant is designed to directly stimulate remaining auditory fibers using electrical current. Still, the goal of each device is to enhance auditory perception.

In this study we looked at accuracy of manner of consonant production, vowel height, and voicing, and assigned a phoneme score as well as a words correct score to each subject. These scores were based on subject performance on a half list of the Phonetically Balanced Kindergarten (PBK) open-set speech perception test (Haskins, 1949). Open-set testing is considered to be one of the most difficult types of tests because no pictures or choices are provided. To perform on open-set tests, users need a device that will maximally enhance their speech perception abilities. However, device alone does not account for one's speech perception success.

Educational background is one of many variables that can have a significant influence on an individual's speech perception ability. We controlled for this by eliminating educational differences from the study. All of the subjects in the study were students at Central Institute for the Deaf (CID) in St. Louis, which is an oral communication school primarily serving profoundly hearing impaired children. Each student at CID participates in a similar educational program, thereby eliminating any effects that education may have on speech perception abilities (Geers and Moog, 1994).

The amount of residual hearing a child has also influences speech perception abilities. Our cochlear implant group had a mean better ear speech frequency average around 112dBHL while our hearing aid group had a mean better ear speech frequency average around 94dBHL. With an average of 18dB more residual hearing, our hearing aid group appears to be similar to the hearing aid plus group described by Geers and Moog (1994).

With rapidly advancing technology in cochlear implants, the need to evaluate performance among implant users has become increasingly important. The introduction of the Spectra 22 Speech Processor in 1994 prompted researchers to begin looking at differences in speech perception between implant users who use different speech coding strategies. Our cochlear implant group consisted of 7 Mini Speech Processor (MSP) users and 11 Spectra 22 Speech Processor users (Spectra). The MSP subjects used the MPEAK speech coding strategy on their processor, which is a feature extraction strategy. The Spectra subjects used the SPEAK speech coding strategy on their processor, which is a spectral peak filterbank strategy. SPEAK was designed to exceed MPEAK by providing more redundancy of speech information and by improving one's ability to perceive speech in noisy situations. It also allows timing information to be perceived more readily. Because each device may enhance different spectral cues, we divided our cochlear implant group into two subgroups -- SPEAK users and MPEAK users. It is not in the scope of this paper to discuss the specific differences in devices and coding strategies. However, Staller, Beiter, and Brimacombe (1994) have discussed this information in detail.

The primary interest of this study is to learn which speech features are most easily perceived by users of each device, and if the device significantly improves one's speech perception ability. According to information from a study conducted with adult cochlear implant users, we can expect the SPEAK users to perform significantly better on average than the MPEAK users for monosyllabic word perception. Skinner et al (1994) found SPEAK scores to be about 10% better than MPEAK scores for phoneme, word, and sentence perception. She also found that 80% of the adult cochlear implant subjects she tested preferred the SPEAK speech coding strategy over the MPEAK speech coding strategy. We can also expect the cochlear implant subjects to perform on average as well as or better than the hearing aid subjects. These predictions are based on the results of Geers and Brenner(1994), who found performance to be similar for cochlear implant subjects and hearing aid plus subjects.

METHOD

SUBJECTS:

Subjects included 9 elementary school children from CID who used hearing aids binaurally, 11 elementary school children from CID who used the Nucleus 22 Channel Cochlear Implant with the SPEAK speech coding strategy in the Spectra 22 speech processor, and 7 elementary school children from CID who used the Nucleus 22 Channel Cochlear Implant with the MPEAK speech coding strategy in the Mini Speech Processor (MSP). The ages of the children ranged from 4 years, 9 months to 15 years, 4 months. Subjects included a mixture of sexes, races, and ethnic backgrounds. All subjects had congenital severe to profound bilateral hearing losses and were assumed to be in good health at the time of the test. Better ear speech frequency averages (500, 1000, and 2000Hz) for all subjects ranged from 86dBHL to 116dBHL. Hearing aid subjects had considerably better hearing thresholds that averaged between 90dBHL and 100dBHL while cochlear implant subjects had hearing thresholds that exceeded 100dBHL. All subjects were initially aided with conventional linear hearing aids between the ages of 6 months and 3 years, 9 months. Age of implantation for cochlear implant subjects ranged from 2 years, 5 months to 12 years, 9 months. All hearing aid subjects wore binaural conventional linear hearing aids. Specific requirements of cochlear implant subjects included the following: 1)all cochlear implant subjects must be implanted for a minimum of 1 year before test date, 2)no additional hearing devices may be used in non-implanted ear, and 3)SPEAK speech coding strategy on Spectra 22 Processor must be used by SPEAK subjects for a minimum of 6 months before test date. Individual information and group means and standard deviations of background information are listed in Tables 1 and 2. Individual information and group means and standard deviations of duration of processor use are listed in Tables 3 and 4.

MATERIALS:

A sound-treated chamber was the testing site where a computer program of the PBK was used to administer the test. A pre-recorded voice delivered the words through a loud speaker in the room at a conversational level. School files were used to access background information for all subjects and past test score sheets for four subjects.

PROCEDURE:

Twenty-three of the 27 subjects were administered the first 25 words from the PBK list 1 by an audiologist and/or audiology practicum student. For the remaining 4 subjects, school files were used to access and evaluate past PBK test score sheets. For all subjects, 25 target PBK words were presented at a conversational level (70-73dBSPL) using a pre-recorded voice delivered through a Macintosh computer. Subjects were required to repeat the presented word. Subject responses were recorded on paper by the examiner and later transcribed into IPA and analyzed phonemically. Table 5 lists the PBK words used and their accepted transcriptions. Table 6 displays the breakdown of the consonants and vowels of the portion of the PBK List 1 used. The first step was to determine the number of words and phonemes each subject got correct. Next, subject responses were analyzed to determine accuracy in vowel height, manner of consonant production, and voicing. The accepted vowel height chart can be found on Table 7, and the accepted consonant manner and voicing chart can be found on Table 8.

A consonant matrix was used to score individual phonemes for accuracy in manner of articulation. For evaluation and scoring, fricatives and affricates were combined into one manner category, as were glides and liquids. Manner of production was scored as correct when the subject produced a phoneme of similar manner in the target position. Voicing was scored as correct when the subject produced any phoneme of similar voicing in the target position. Vowels were scored as correct when the subject produced a vowel of similar height in the target position. Each consonant and vowel category was required to have a minimum of 6 targets to be scored. Diphthongs were the only category eliminated, and this was because they had fewer than 6 targets. Table 9 displays overall percentages correct for phonemes, words, manner of consonant production, vowel height, and voicing for each subject. Table 10 shows the means and standard deviations for these aspects for each subject group.

RESULTS

Data were analyzed for each group using an analysis of variance. The cochlear implant group seemed to perform similarly to the hearing aid group. No significant advantage or disadvantage was found for the hearing aid group as compared to the cochlear implant group. Within the cochlear implant group, little significant advantage was found for the SPEAK strategy over the MPEAK strategy. The only feature found to be significant was the semivowel category where the SPEAK strategy (67.3%) performed significantly better than the MPEAK strategy (41.4%) [$F=3.30$, $p < .05$]. Figure 1 charts percentages correct for stops, fricatives/affricates, nasals, and semivowels for each group.

[Insert Figure 1 about here.]

Figure 2 charts percentages correct for vowel perception for each group. No significance was found for high, mid, or low vowels.

[Insert Figure 2 about here.]

Figure 3 charts percentages correct for words and phonemes for each group. No significance was found for either of these features.

[Insert Figure 3 about here.]

Confusion matrices for manner of production were constructed for each group. Raw data is shown in Figures 4, 5, and 6 while percent substitution data is shown in Figures 7, 8, and 9.

[Insert Figures 4, 5, and 6 about here.]

[Insert Figures 7, 8, and 9 about here.]

Substitutions were considered remarkable if they were made at least 20% of the time for a specific phoneme. Errors were similar among the two cochlear implant speech coding strategies, as both strategies showed errors with the phonemes /p/, /g/, /v/, /ʧ/, and /w/. Both groups frequently substituted /d/ for /g/, /f/ for /p/, and /ʃ/ for /ʧ/. The SPEAK group also used /b/ as a substitution for /p/. For all common substitution errors, the

MPEAK group made a higher percentage of errors than the SPEAK group. For /w/, the MPEAK group most often used /f/ as a substitution while the SPEAK group most often used /r/ as a substitution. For /v/, the MPEAK group most often used /g/ as a substitution while the SPEAK group most often used /d/ as a substitution. Additional substitution patterns exhibited by the MPEAK group included the substitution of /ʃ/ for /z/ and /s/. Additional substitution patterns exhibited by the SPEAK group included the substitution of /b/ for /f/ and the substitution of /k/ for /h/. SPEAK subjects did as well as or better than MPEAK subjects for percent correct production of exact consonants for all consonants except /f/ and /w/. MPEAK subjects performed 1% better for /f/ and 2% better for /w/. Although MPEAK subjects performed better for /w/ for exact phoneme response, their primary substitution was /f/. The primary substitution made by SPEAK users was /r/, which we considered "correct" because it is within the semivowel category.

The hearing aid group seemed to share only a few errors with the cochlear implant group -- /d/ for /g/ and /ʃ/ for /tʃ/. The hearing aid group, however, did show considerable substitution of /b/ for /f/, which was also demonstrated by the SPEAK group. Additional substitution patterns exhibited by the hearing aid group included the substitution of /s/ for /θ/ and /r/ for /l/. Table 11 shows the number of targets for each group and the primary substitutions for each group.

[Insert Table 11 about here.]

Excellent phoneme recognition (≥ 50%) included /b/, /m/, and /r/ for the hearing aid group and /b/ and /r/ for the SPEAK group. The MPEAK group did not show correct phoneme identification ≥50% for any specific phoneme.

Three of the cochlear implant subjects were part of both the MPEAK group and the SPEAK group. For each subject testing with the MPEAK strategy occurred prior to testing with the SPEAK strategy. However, testing with the SPEAK strategy in each case occurred between 7 and 10 months after testing with the MPEAK strategy. There were no changes in hearing sensitivity between test dates. The only features that seemed to be perceived as well or better using SPEAK were nasals (by all 3 subjects), semivowels (by 2 of the 3 subjects), and low vowels (by all 3 subjects). MPEAK seemed to provide more benefit to all three subjects for overall vowel height, high vowels, mid vowels, stops, and fricatives/affricates. Scores for each of the three subjects using MPEAK as compared to SPEAK can be found in Table 12.

[Insert Table 12 about here.]

DISCUSSION

This study found both the hearing aid group and the cochlear implant group to perform similarly. This means that the implant users performed as well as the hearing aid users who had 90-100dBHL thresholds. This supports the use of hearing aids rather than cochlear implants with children who have 90-100dBHL losses, and serves as evidence that profoundly deaf children can perform well with limited residual hearing.

Within the implant group, however, we found a semivowel advantage for SPEAK over MPEAK. The significance of semivowels implies that there is a large difference between the way the cochlear implant speech coding strategies handle the liquid and glide features. For our study, semivowels included /r/, /l/, and /w/. There were no stimuli for /j/. We found the most distinct differences to be between strategies for the phonemes /r/ and /w/. Figures 10, 11, 12, and 13 show the electrodograms for each coding strategy for the words "rat" and "ways". Figure 10 represents the coding strategy for the stimulus "rat" using SPEAK while figure 11 represents the coding strategy for the stimulus "rat" using MPEAK.

[Insert Figure 10 about here.]

[Insert Figure 11 about here.]

Figure 12 represents the coding strategy for the stimulus "ways" using SPEAK while figure 13 represents the coding strategy for the stimulus "ways" using MPEAK. Additional electrodograms can be seen in the Appendix.

[Insert Figure 12 about here.]

[Insert Figure 13 about here.]

The electrodograms for each strategy were produced using the MAP of a subject who had full insertion and who used the maximum number of possible electrodes. The electrodograms help to account for differences in perception between SPEAK and MPEAK. One can see that words coded using SPEAK have better defined formant structures than words using MPEAK. Words using SPEAK also have more electrodes stimulated, which provides frequency redundancy and improves the listener's ability to identify words. Due to the nature of a feature extraction coding strategy, MPEAK electrodograms generally have more sparse firing patterns and therefore provide less information.

The semivowels are probably better perceived by SPEAK users because the SPEAK strategy allows for timing cues, stress cues, and duration cues to be more readily coded and transmitted to the user while the MPEAK strategy only codes and transmits specific parts of the stimulus. Additional information is beneficial for correctly identifying semivowels because they can be difficult to distinguish. The formant structures of /r/ and /l/ are very similar. They have similar first and second formant structures, and differ primarily in third formant structures. The third formant of /l/ remains steady while the third formant of /r/ rises to the following vowel (Borden & Harris, 1985). With this type of detail necessary to distinguish the sounds, it is not surprising that the additional temporal cues and frequency redundancy provided by SPEAK allows users to perceive speech better.

Skinner et al. (1994) found the SPEAK strategy to enhance speech perception of semivowels. It was also found that both SPEAK and MPEAK users made considerable /r/ for /l/ confusions. This finding is consistent with the results from our study, as we found /r/ to be the most frequent substitution made for /l/ by both SPEAK and MPEAK users as well as hearing aid users. Although substitutions were made, Skinner et al. found SPEAK users to correctly identify /l/ about 10% better than MPEAK users (40% correct identification for MPEAK verses 50% for SPEAK). We found SPEAK users to correctly identify /l/ about 23% better than MPEAK users (11% correct identification for MPEAK verses 34% for SPEAK).

Other phoneme confusions noted by Skinner et al. (1994) included /t/ for /p/ and /n/ for /m/ by MPEAK users and /k/ for /p/ and /l/ for /m/ by SPEAK users. We also found cochlear implant subjects to produce other phonemes in the place of /p/. Our MPEAK subjects often substituted /f/ for /p/ while our SPEAK subjects often substituted /f/ or /b/ for /p/. (For our study, the substitution of /b/ for /p/ was recorded as a correct response because /b/ and /p/ had the same manner of production.) We did not find many confusions for /m/.

For the three subjects who served in both the MPEAK and SPEAK groups, the SPEAK strategy seemed to improve the user's ability to correctly identify nasals, semivowels, and low vowels. This is also probably due to the temporal cues provided by SPEAK and can be attributed to both the SPEAK strategy itself and the subjects' training since all three subjects showed similar patterns of benefit. The subject who had used SPEAK for the longest duration had the fewest features that were better coded using MPEAK. This implies that given more time to train with SPEAK, subjects may have considerable improvement in feature perception. At this point the nasals, semivowels, and vowels all seem to show considerable improvement using a particular strategy. Nasals, semivowels, and low vowels were typically improved using SPEAK while high vowels, mid vowels, and overall vowel height were typically improved using MPEAK.

When Skinner et al. (1994) looked at performance of adult cochlear implant subjects with the MPEAK verses the SPEAK speech coding strategy they found SPEAK to provide a significant improvement in both word and phoneme scores. We used the condition that they got the best results in, but we did not see a word or phoneme significance. This is probably because our subjects were children, who did not score as high. Our subjects had low word recognition scores, but they showed a similar increase for phoneme scores over word scores when compared with adults. Phoneme scores for the children were about 22% higher than word scores while phoneme scores for the adults were about 25% higher than word scores. It is theorized that deaf children do not have as broad of vocabularies as do deaf adults and are not as good at guessing. They try to say what they hear rather than applying it to their knowledge of words and devising a logical response. Therefore, open-set testing is considerably more challenging for deaf children than it is for deaf adults. Should further research be conducted in this area, the inclusion of more stimuli would prove beneficial in establishing valid and reliable results. This study should serve as a foundation for further investigations.

References

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Table 1

AGES AND THRESHOLDS OF SUBJECTS

HEARING AID SUBJECTS(9)

SUBJECT	C.A. @ TEST	BETTER EAR SFA	AGE AIDED	AGE IMPLANTED
1)	10.6	91	1.10	NA
2)	6	93	1.5	NA
3)	11.11	93	2	NA
4)	9.2	95	3	NA
5)	6.3	86	1.11	NA
6)	9.3	90	1.9	NA
7)	12.5	96	3.9	NA
8)	15.4	101	.10	NA
9)	12.4	98	2.9	NA
AVG(YEARS):	10.4	93.7	2.2	NA

SPEAK SUBJECTS(11)

SUBJECT	C.A. @ TEST	BETTER EAR SFA	AGE AIDED	AGE IMPLANTED
10)	10.7	116	1.4	4.5
11)	6.11	108	1.9	3.3
12)	14.6	116	1.5	7
13)	4.9	116	1	2.8
14)	6.10	110	.11	2.9
15)	9.9	116	2.2	2.5
16)	9	108	1.3	4
17)	9.2	116	.8	7.6
18)	9.8	115	.11	6.9
19)	9.10	111	1.1	3.11
20)	14.3	91	1.2	12.9
AVG(YEARS):	9.7	111.2	1.3	5.3

MPEAK SUBJECTS(7)

SUBJECT	C.A. @ TEST	BETTER EAR SFA	AGE AIDED	AGE IMPLANTED
21)	6.3	110	.11	2.9
22)	11.6	116	2.6	3.2
23)	13.11	116	1.5	7
24)	8.10	115	.11	6.9
25)	7	113	1.2	3.2
26)	6.2	115	.6	3
27)	7.11	98	1.3	6.10
AVG(YEARS):	8.10	111.9	1.3	5.3

Table 2

AGES AND THRESHOLDS OF SUBJECTS

		AGE	BETTER EAR SFA	AGE AIDED	AGE IMPLANTED
HEARING AID	X	10.4	93.7	2.2	NA
	S.D.	2.10	4.2	.10	NA
SPEAK	X	9.7	111.2	1.3	5.3
	S.D.	2.9	7.1	.5	2.11
MPEAK	X	9.0	111.9	1.3	4.8
	S.D.	2.8	6.0	.7	1.11

Table 3

DURATION OF IMPLANT USE

HEARING AID SUBJECTS(9)

SUBJECT	DURATION MSP USE	DURATION SPECTRA USE
1)	NA	NA
2)	NA	NA
3)	NA	NA
4)	NA	NA
5)	NA	NA
6)	NA	NA
7)	NA	NA
8)	NA	NA
9)	NA	NA
AVG(YEARS):	NA	NA

SPEAK SUBJECTS(11)

SUBJECT	DURATION MSP USE	DURATION SPECTRA USE
10)	4.9 years	1.5 years
11)	3.2	.6
12)	6.11	.7
13)	1.7	.6
14)	3.7	.6
15)	6.10	.6
16)	4.3	.9
17)	1.2	.6
18)	2.2	.9
19)	5.4	.7
20)	1.0	.6
AVG(YEARS):	3.9	.8

MPEAK SUBJECTS(7)

SUBJECT	DURATION MSP USE	DURATION SPECTRA USE
21)	3.7 years	NA
22)	8.4	NA
23)	6.11	NA
24)	2.1	NA
25)	3.10	NA
26)	3.2	NA
27)	1.1	NA
AVG(YEARS):	4.1	NA

Table 5

PBK LIST 1 WORDS & TRANSCRIPTIONS

1.	PLEASE	/pliz/
2.	GREAT	/gret/
3.	SLED	/slEd/
4.	PANTS	/pænts/
5.	RAT	/ræt/
6.	BAD	/bæd/
7.	PINCH	/pIntʃ/
8.	SUCH	/sʌtʃ/
9.	BUS	/bʌs/
10.	NEED	/nid/
11.	WAYS	/wez/
12.	FIVE	/fa͡iv/
13.	MOUTH	/ma͡uθ/
14.	RAG	/ræg/
15.	PUT	/pUt/
16.	FED	/fEd/
17.	FOLD	/fold/
18.	HUNT	/hʌnt/
19.	NO	/no/
20.	BOX	/baks/
21.	ARE	/ar/
22.	TEACH	/titʃ/
23.	SLICE	/sla͡is/
24.	IS	/Iz/
25.	TREE	/tri/

Table 6

BREAKDOWN OF PBK LIST 1
(83 phonemes)

CONSONANTS
(58 consonants)

STOPS: 22
4 p; 3 b; 7 t; 5 d; 1 k; 2 g;

FRICATIVES/AFFRICATES: 20
3 f; 1 v; 1θ; 7 s; 3 z; 3tʃ; 2 h;

NASALS: 6
1 m; 5 n;

GLIDES/LIQUIDS: 10
4 l; 5 r; 1 w;

[30 voiced consonants & 28 voiceless consonants]

VOWELS
(25 vowels total, but only 22 vowels evaluated)

HIGH VOWELS: 7
4 i; 2 I; 1 U;

MID VOWELS: 9
2 e; 2 E; 2 o; 3ə ;

LOW VOWELS: 6
4æ; 2 a;

DIPHTHONGS: 3
2 $\overline{\text{ai}}$; 1 $\overline{\text{au}}$;
Eliminated b/c less than 6 targets

Table 8

CONSONANT PLACE

MANNER	Bilabial		Dental				Alveolar		Palatal		Velar	
Voicing->	+	-	+	-	+	-	+	-	+	-	+	-
Stop	b	p					d	t			g	k
Fricative			v	f	ð thi	θ thi	z	s		ʃ sh		h
Affricate							dʒ j	tʃ ch				
Nasal	m						n				ŋ ng	
Glide	w								r	j y		
Lateral							l					

Table 9

OVERALL PERCENTAGES CORRECT FOR SUBJECTS

HEARING AID SUBJECTS (9)

SUBJECT	PHONEMES CORRECT	WORDS CORRECT	CORRECT STOPS	CORRECT FRIC/AFF.	CORRECT NASAL	CORRECT GLIDE/LIQ	VOWEL HEIGHT	HIGH VOWEL	MID VOWEL	LOW VOWEL	CORRECT VOICING	CORRECT VOICED	CORRECT VOICELESS
#1	71%	56%	82%	90%	67%	100%	77%	86%	89%	50%	88%	90%	85%
#2	55%	24	59%	74%	17%	90%	73%	71%	78%	67%	75%	67%	85%
#3	42%	12	77%	63%	67%	60%	50%	29%	78%	33%	74%	77%	70%
#4	42%	8	55%	68%	50%	70%	73%	71%	89%	50%	86%	87%	85%
#5	39%	4	59%	53%	33%	50%	64%	43%	67%	83%	67%	60%	74%
#6	35%	12	73%	42%	33%	90%	55%	43%	67%	50%	81%	83%	78%
#7	24%	8	46%	26%	33%	80%	46%	86%	22%	33%	63%	57%	70%
#8	17%	0	64%	21%	17%	20%	50%	43%	67%	33%	54%	47%	63%
#9	9%	0	46%	26%	0%	20%	46%	57%	22%	67%	42%	37%	48%
AVERAGE	(37.1%)	(13.7%)	(62.3%)	(51.4%)	(35.2%)	(64.4%)	(59.3%)	(58.8%)	(64.3%)	(51.8%)	(70%)	(67.2%)	(73.1%)

COCHLEAR IMPLANT SUBJECTS -- SPEAK (11)

SUBJECT	PHONEMES CORRECT	WORDS CORRECT	CORRECT STOPS	CORRECT FRIC/AFF	CORRECT NASAL	CORRECT GLIDE/LIQ	VOWEL HEIGHT	HIGH VOWEL	MID VOWEL	LOW VOWEL	CORRECT VOICING	CORRECT VOICED	CORRECT VOICELESS
#10	89%	76%	91%	84%	67%	90%	100%	100%	100%	100%	95%	93%	96%
#11	43	16	91	47	0	40	64	57	67	67	65	63	67
#12	40	8	59	74	17	80	55	71	33	67	70	67	74
#13	38	8	41	47	33	70	55	57	44	67	54	43	67
#14	37	16	55	58	33	80	76	71	67	83	72	67	78
#15	37	12	46	68	17	80	36	43	33	33	63	57	70
#16	34	4	82	42	17	80	59	43	89	33	74	73	74
#17	32	12	32	37	17	60	59	57	78	33	61	53	70
#18	29	12	46	47	17	40	55	71	33	67	65	57	74
#19	27	0	55	47	0	60	59	43	78	50	53	50	56
#20	23	0	68	32	0	60	64	86	78	17	60	53	67
AVERAGE	(39%)	(14.9%)	(60.5%)	(53%)	(19.8%)	(67.3%)	(62%)	(63.6%)	(63.6%)	(56.1%)	(66.6%)	(61.5%)	(72.1%)

COCHLEAR IMPLANT SUBJECTS -- MPEAK (7)

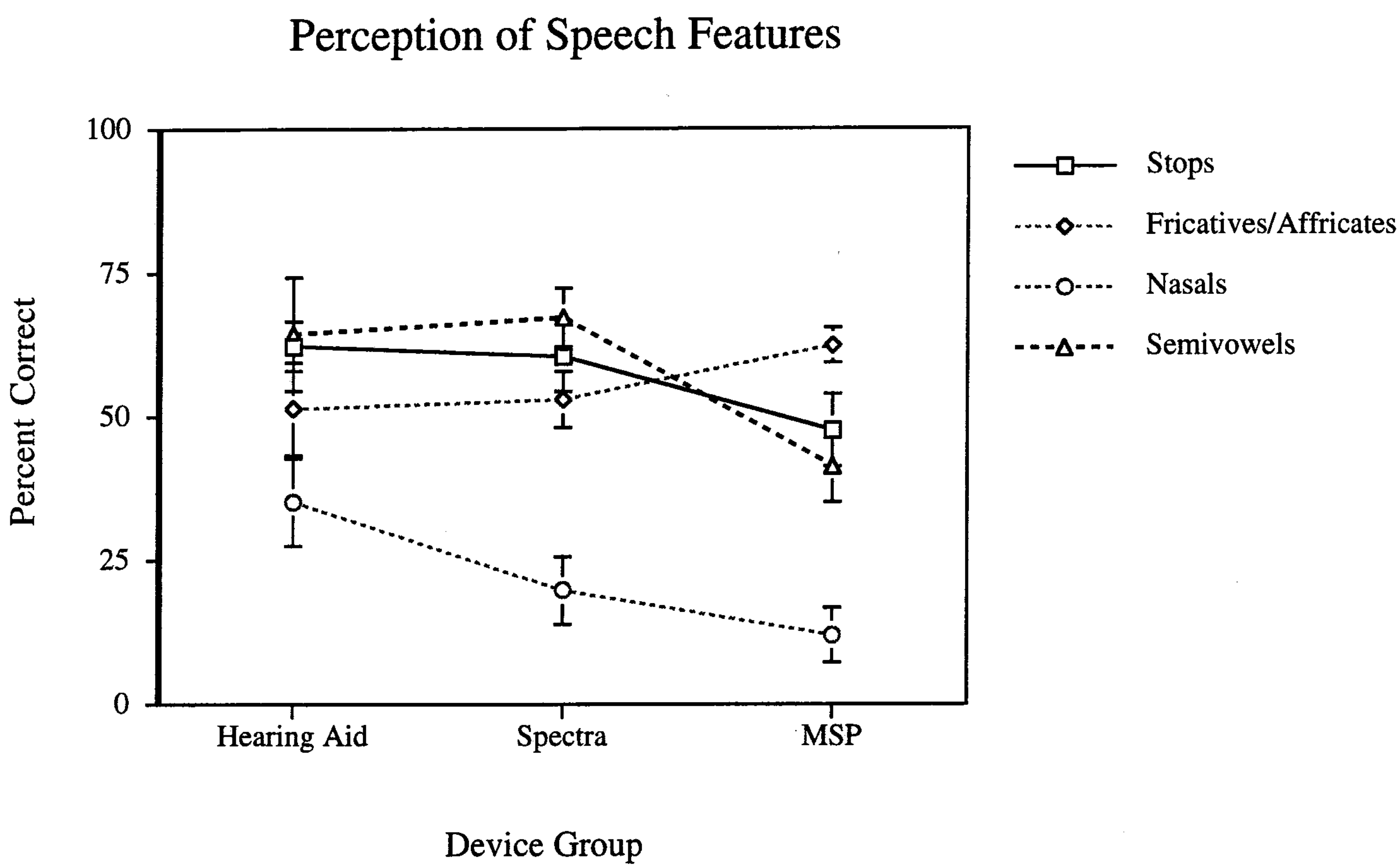
SUBJECT	PHONEMES CORRECT	WORDS CORRECT	CORRECT STOPS	CORRECT FRIC/AFF	CORRECT NASAL	CORRECT GLIDE/LIQ	VOWEL HEIGHT	HIGH VOWEL	MID VOWEL	LOW VOWEL	CORRECT VOICING	CORRECT VOICED	CORRECT VOICELESS
#21	32%	8%	59%	68%	0%	50%	91%	100%	100%	67%	58%	50%	67%
#22	29	4	64	63	33	60	36	43	33	33	61	57	67
#23	28	8	64	68	0	50	64	86	78	17	70	60	82
#24	28	8	46	53	17	50	59	71	56	50	56	50	63
#25	24	4	36	58	17	30	59	71	56	50	47	33	63
#26	16	0	46	74	17	40	50	100	33	17	56	37	78
#27	16	0	18	53	0	10	46	71	44	17	39	20	59
AVERAGE	(24.7%)	(4.6%)	(47.6%)	(62.4%)	(12%)	(41.4%)	(57.9%)	(77.4%)	(57.1%)	(35.9%)	(55.3%)	(43.9%)	(68.4%)

Table 10

OVERALL PERCENTAGES CORRECT FOR SUBJECTS

		PHONEMES CORRECT	WORDS CORRECT	CORRECT STOPS	CORRECT FRIC/AFF	CORRECT NASAL	CORRECT GLIDE/LIQ	VOWEL HEIGHT	HIGH VOWEL	MID VOWEL	LOW VOWEL	CORRECT VOICING	CORRECT VOICED	CORRECT VOICELESS
HEARING AID	X	37.1 %	13.7 %	62.3 %	51.4 %	35.2 %	64.4 %	59.3 %	58.8%	64.3 %	51.8%	70%	67.2%	73.1 %
	S.D.	19	17.5	12.9	24.3	22.8	29.6		20.7	25.5	17.7	15.2		
SPEAK	X	39	14.9	60.5	53	19.8	67.3	62	63.6	63.6	56.1	66.6	61.5	72.1
	S.D.	17.6	21	20.1	16.2	19.5	16.8		18.4	24.1	25.1	11.6		
MPEAK	X	24.7	4.6	47.6	62.4	12	41.4	57.9	77.4	57.1	35.9	55.3	43.9	68.4
	S.D.	6.4	3.6	16.8	8.1	12.6	16.8		20	24.5	20.2	9.9		

Figure 1



Perception of Speech Features
100
75
50
25
0
Percent Correct
Hearing Aid
Spectra
MSP
Device Group
Stops
Fricatives/Affricates
Nasals
Semivowels

Figure 2

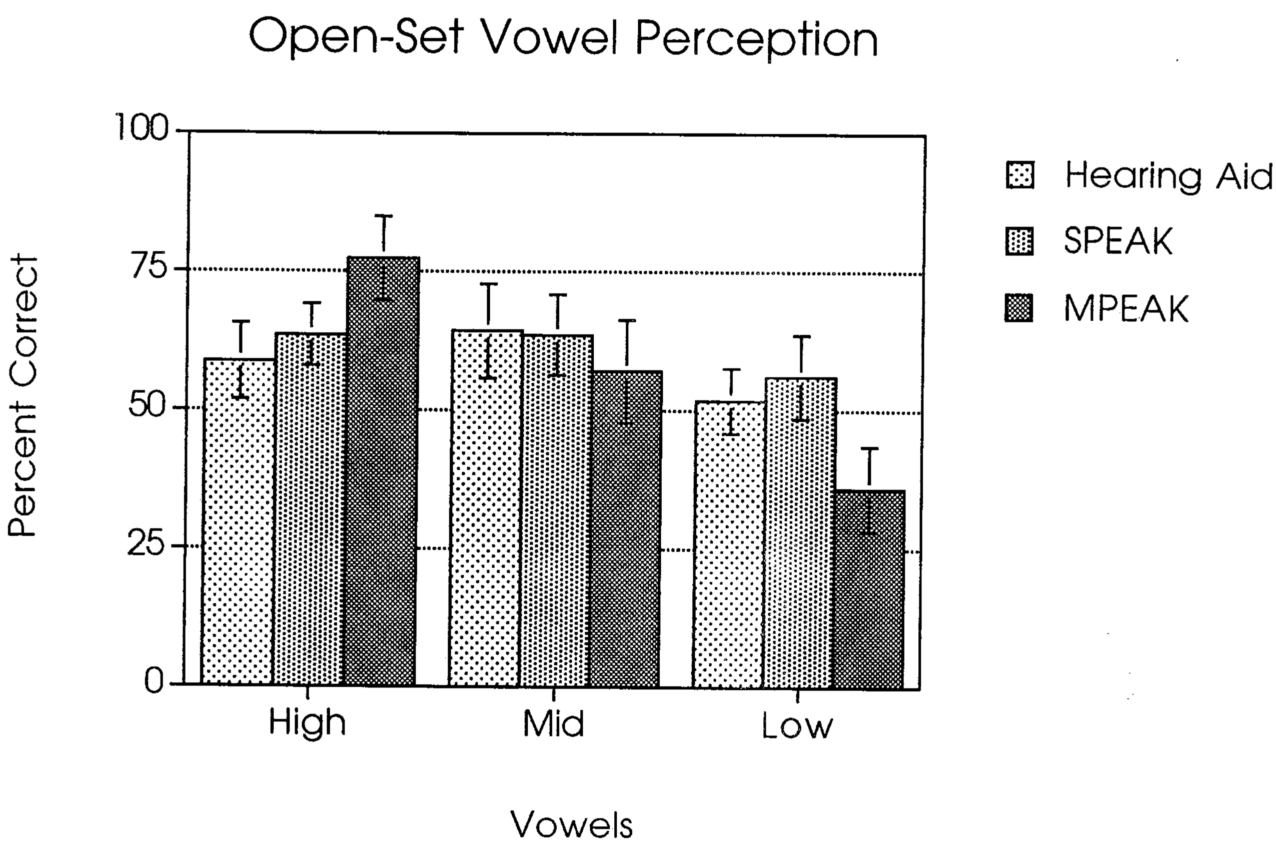

Open-Set Vowel Perception
100
75
50
25
0
Percent Correct
High
Mid
Low
Vowels
Hearing Aid
SPEAK
MPEAK

Figure 3

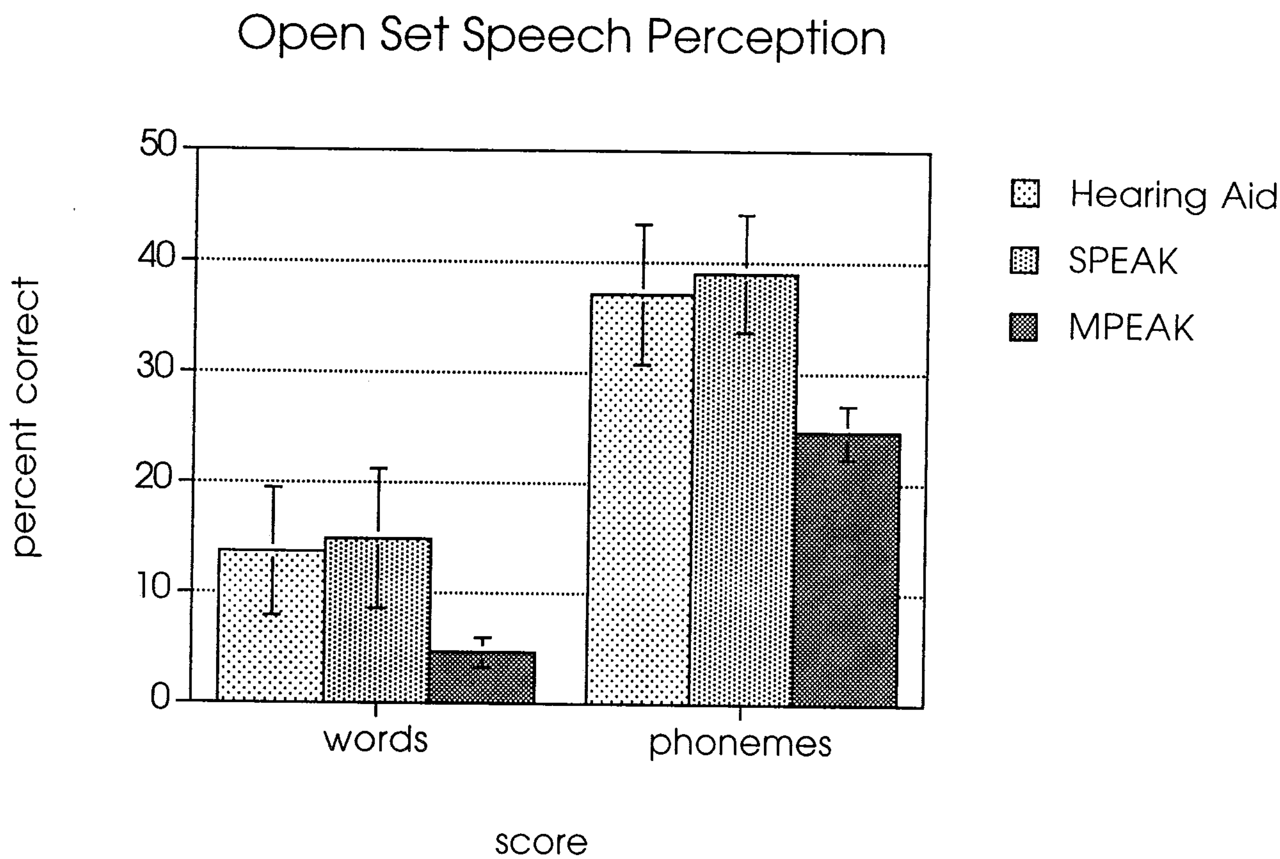

Open Set Speech Perception
50
40
30
20
10
0
percent correct
words
phonemes
score
Hearing Aid
SPEAK
MPEAK

Figure 4

Hearing Aids [Raw Scores]

Response

Stimulus	b	p	d	t	g	k	v	f	z	s	ð	θ	ʃ	h	dʒ	tʃ	m	n	r	w	l	OMIT
b	18		4	1		1		1			1									1		0
p	7	5	2	2		7		3		3		1		1					2			3
d	3		19	2					2								2	6	4		2	5
t	1	2	1	22		11		2		4			4	1		5			1			9
g	1		5		3	4				1								1				3
k						2											1					6
v					1		2		1									1	1		1	2
f	8					5		4		3				3			1				1	2
z			3	1					6	1			5		1			3				7
s	1	1	1	9	1	4	1	1		16			8			7	2	1	2		1	7
θ				1		1				3		3										1
h		2	1	2		1								4								8
tʃ		1		4		3							6		2	10						1
m								1						1			7					0
n		1		2		2	1	1		1							2	10			1	24
r	2				1	1											2		24	4	4	7
w	1			1	2															3	1	1
l																			8	4	10	14

Figure 5

SPEAK [Raw Scores]

Response

Stimulus

	b	p	d	t	g	k	v	f	z	s	ð	θ	ʃ	h	dʒ	tʃ	m	n	r	w	l	OMIT
b	24	1				1		1		1								1		1		3
p	9	6		2	2	2		11		3							1		1	5		2
d			16	3	2	4				1		2	2				3	4		7	2	9
t	2	1	3	32	1	13				2			5			1		2	1	1	1	12
g	2	1	5	3	6	1																4
k						4													1			6
v			3				1											1	2	1	1	2
f	9	1		2		6		6		3			1	3								2
z			1	2		1			8	1			6		1	2		2	6			3
s	1	1	1	12		2			1	27			14		1	6						11
θ				1		2						3				1					2	2
h						7								4						1		10
tʃ		2		5		2							8			14						2
m	1		1														5					4
n	5	1			2	3			1					3			1	6	1			32
r	2		1					3										2	41	3	1	2
w	1	2		1															41	3		0
l				2	1	1													4	3	15	18

Figure 6

MPEAK [Raw Scores]

Response

Stimulus

	b	p	d	t	g	k	v	f	z	s	ɣ	θ	ʃ	h	dʒ	tʃ	m	n	r	w	l	OMIT
b	7	2						4							1					1		6
p		4		1		1		9					1	1					1	2		8
d			7	4	3	2							2		1	1		2	1	1		11
t		1		9	3	6		5		1			3			2						19
g		1	5	1	1	1		1														4
k																						7
v			1		3														1			2
f	3	1	1			2		4					1	1		1						7
z			1						1	1			9		1	1		1				6
s				1						12			15			5						16
θ		1										1					1			1	2	1
h		1		1		2		1						1								8
tʃ				1				1					9			5						5
m		1			1	1								1			1					2
n	2			1				2									3	1		1		25
r	1	1	2	1		1		1											16			12
w	1							3												2		1
l		1																	2	1	3	21

Figure 7

Hearing Aids [Percent Scores]

Response

Stimulus

	b	p	d	t	g	k	v	f	z	s	ʒ	θ	ʃ	h	dʒ	tʃ	m	n	r	w	l	OMIT
b	67		15	4		4		4			4									4%		0
p	19	14	6	6		19		8		8		3		3					6			8
d	7		42	4					4								4	13	9		4	13
t	2	3	2	35		17		3		6			6	2		7			2			15
g	6		28		17	22												6				15
k						22											11					67
v					11		22		11									11	11		11	23
f	30					19		15		11				11			4				4	6
z			11	4					22	4			19		4			11				25
s	2	2	2	14	2	6	2	2		25			13			11	3	2	3		2	9
θ				11		11				33		33										12
h		11	6	11		6								22								44
tʃ		4		15		11							22		7	37						4
m								11						11			78					0
n		2		4		4	2	2		2							4	22			2	56
r	4				2	2											4		53	9	9	17
w	11			11	22															33	11	12
l																			22	11	28	39

Figure 8

SPEAK [Percent Scores]

Response

Stimulus

	b	p	d	t	g	k	v	f	z	s	ɣ	θ	ʃ	h	dʒ	tʃ	m	n	r	w	l	OMIT
b	73	3				3		3		3								3		3		9
p	20	14		5	5	5		25		7							2		2	11		4
d			29	5	4	7				2		4	4				5	7	13		4	16
t	3	1	4	42	1	17				3			6			1		3	1	1	1	16
g	9	5	23	14	27	5																17
k						36													9			55
v			27				9											9	18	9	9	19
f	27	3		6		18		18		9			3	9								7
z			3	6		3			24	3			18		3	6		6	18			10
s	1	1	1	16		3			1	35			18		1	8						15
θ				9		18						27				9					18	19
h						32								18						5		45
tʃ		6		15		6							24			42						7
m	9		9														45					37
n	9	2			4	6			2					6			2	11	2			56
r	4		2					6										4	75	6	2	1
w	9	18		9															36	27		1
l				5	2	2													9	7	34	41

Figure 9

MPEAK [Percent Scores]

Response

Stimulus

	b	p	d	t	g	k	v	f	z	s	ð	θ	ʃ	h	dʒ	tʃ	m	n	r	w	l	OMIT
b	33	10						19							5					5		28
p		14		4		4		32					4	4					4	7		27
d			20	11	9	6							6		3	3		6	3	3		30
t		2		18	6	12		10		2			6			4						40
g		7	36	7	7	7		7														29
k																						100
v			14		43														14			29
f	14	5	5			10		19					5	5		5						32
z			5						5	5			43		5	5		5				27
s				2						24			31			10						33
θ		14										14					14			14	29	15
h		7		7		14		7						7								58
tʃ				5				5					43			24						23
m		14			14	14								14			14					30
n	6			3				6									9	3		3		70
r	3	3	6	3		3		3											46			33
w	14							43												29		14
l			4																7	4	11	74

Table 11

Frequent Errors

STIMULUS	TOTAL # HA	TOTAL # SPEAK	TOTAL # MPEAK	# CORRECT HA	# CORRECT SPEAK	# CORRECT MPEAK	MOST FREQ. ERROR HA	MOST FREQ. ERROR SPEAK	MOST FREQ. ERROR MPEAK	2ND MOST FREQ. ERROR HA	2ND MOST FREQ. ERROR SPEAK	2ND MOST FREQ. ERROR MPEAK	# OMITTED HA	# OMITTED SPEAK	# OMITTED MPEAK
/b/	27	33	21	18	24	7	d(4)		f(4)			p(2)	0	3	6
/p/	36	44	28	5	6	4	b/k(7)	f(11)	f(9)	f/s(3)	b(9)	w(2)	3	2	8
/d/	45	55	35	19	16	7	n(6)	r(7)	t(4)	r(4)	k/n(4)	g(3)	5	9	11
/t/	63	77	49	22	32	9	k(11)	k(13)	k(16)	tʃ(5)	ʃ(5)	f(5)	9	12	19
/g/	18	22	14	3	6	1	d(5)	d(5)	d(5)	k(4)	t(3)		3	4	4
/k/	9	11	7	2	4	0	m(l)	r(l)					6	6	7
/v/	9	11	7	2	1	0		d(3)	g(3)		r(2)	d/r(1)	2	2	2
/f/	27	33	21	4	6	4	b(8)	b(9)	b(3)	k(5)	k(6)	k(2)	2	2	7
/z/	27	33	21	6	8	1	ʃ(5)	ʃ/r(6)	ʃ(9)	t(3)			7	3	6
/s/	63	77	49	16	27	12	t(9)	ʃ(14)	ʃ(15)	ʃ(8)	t(12)	t(15)	7	11	16
/θ/	9	11	7	3	3	1	s(3)	k/l(2)	l(2)	t/k(1)	t/tʃ(1)		1	2	1
/h/	18	22	14	4	4	1		k(7)	k(2)		w(1)		8	10	8
/tʃ/	27	33	21	10	14	5	ʃ(6)	ʃ(8)	ʃ(9)	t(4)	t(5)	t/f(1)	1	2	5
/m/	9	11	7	7	5	1		b/d(1)					0	4	2
/n/	45	55	35	10	6	1		b(5)	m(3)		k/h(3)	b/f(2)	24	32	25
/r/	45	55	35	24	41	16		f/w(3)	d(2)		n/b(2)		7	2	12
/w/	9	11	7	3	3	2	g(2)	r(4)	f(3)		p(2)	b(1)	1	0	1
/l/	36	44	28	10	15	3	r(8)	r(4)	r(2)	w(4)	w(3)	w/p(1)	14	18	21

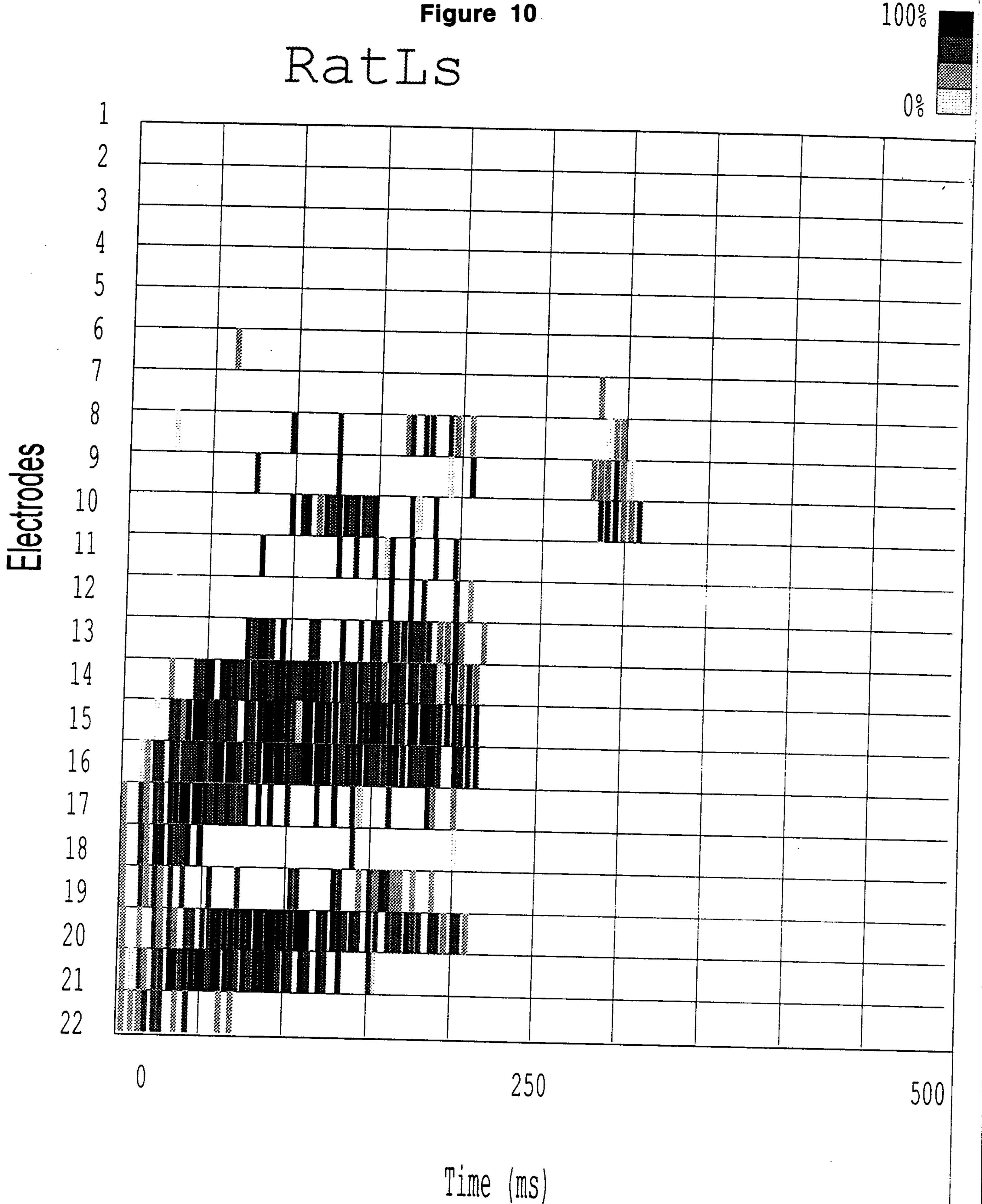
*Errors were not included for some sounds when more than 2 substitutions were made an equal number of times for the specific sound.
**When the error and the stimulus had the same manner of production, the error was recorded as a correct response.

Table 12

Subjects Included in SPEAK and MPEAK

Subject	Strategy	Age at Test	Duration Use at Test	Phonemes Correct	Words Correct	Stops Correct	Fric/Aff Correct	Nasals Correct	Semivowels Correct	Vowel Height	High Vowels	Mid Vowels	Low Vowels	Voicing	Voiced	Voiceless
CD	MPEAK	6.3	3.7	32%	8%	59%	68%	0%	50%	91%	100%	100%	67%	58%	50%	67%
	SPEAK	6.10	.6	37	16	55	58	33	80	76	71	67	83	72	67	78
AH	MPEAK	13.11	6.11	28	8	64	68	0	50	64	86	78	17	70	60	82
	SPEAK	14.6	.7	40	8	59	74	17	80	55	71	33	67	70	67	74
RR	MPEAK	8.10	2.1	28	8	46	53	17	50	59	71	56	50	56	50	63
	SPEAK	9.8	.9	29	12	46	47	17	40	55	71	33	67	65	57	74

Figure 10



RatLs
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)

Figure 11

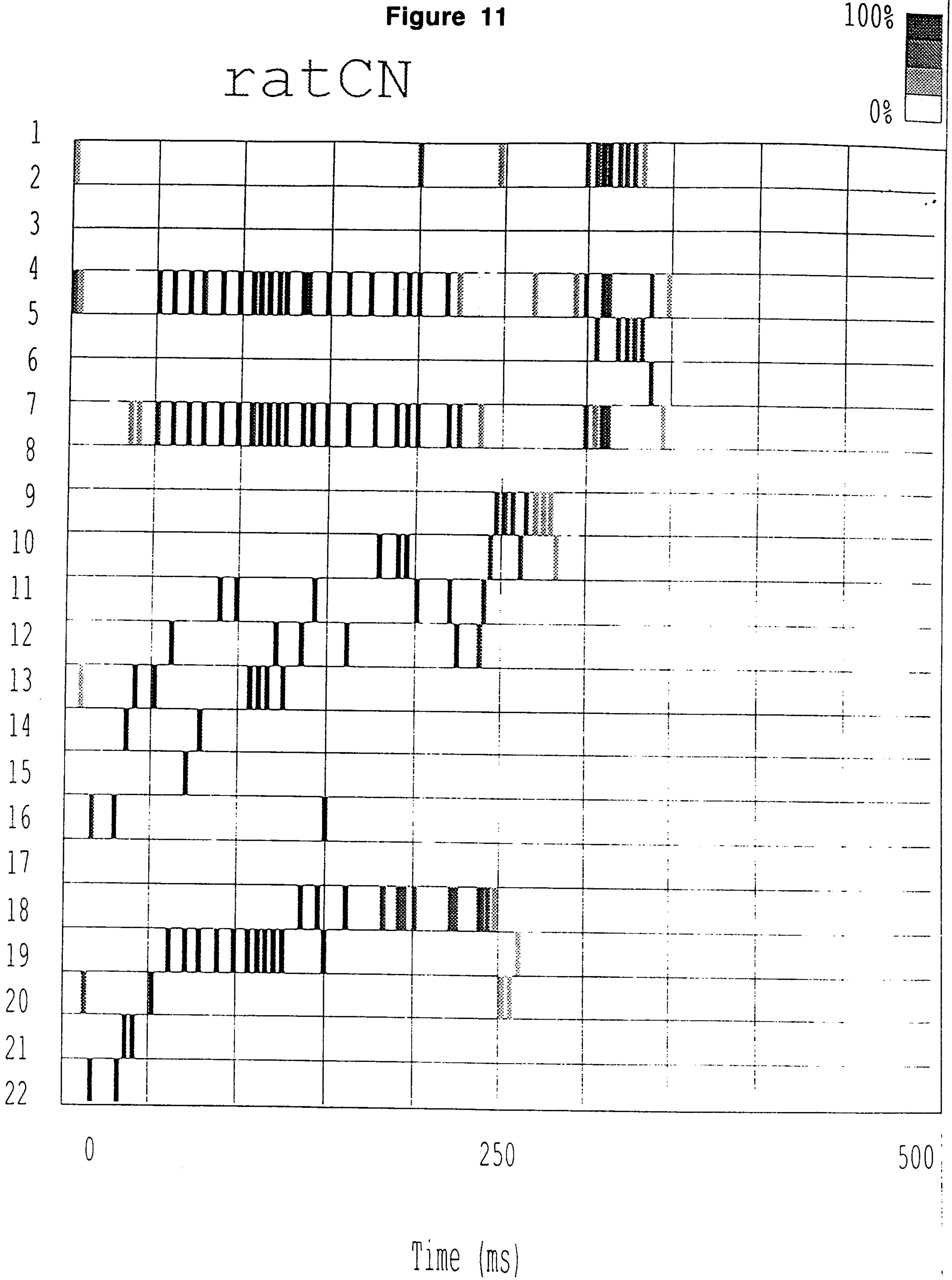
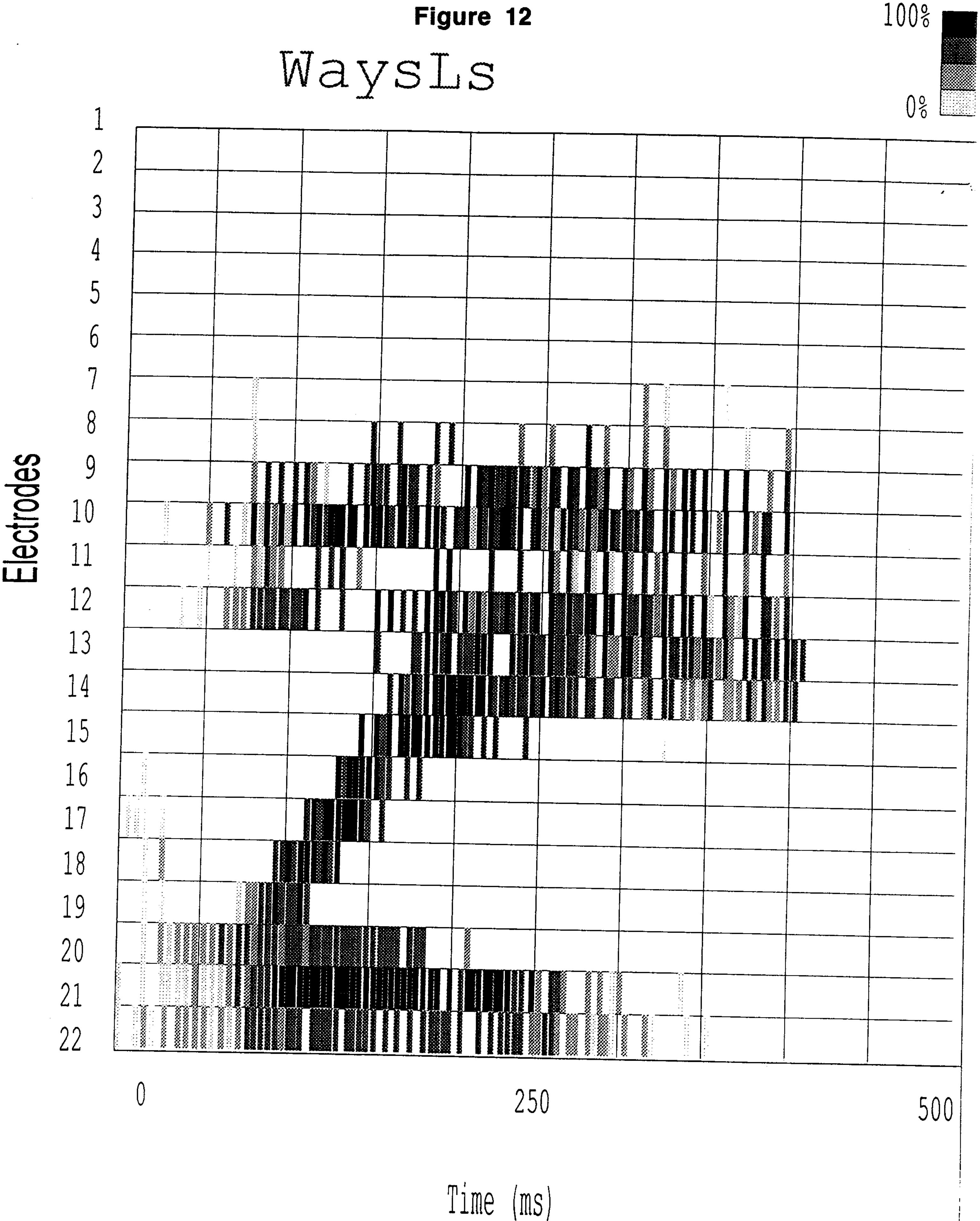
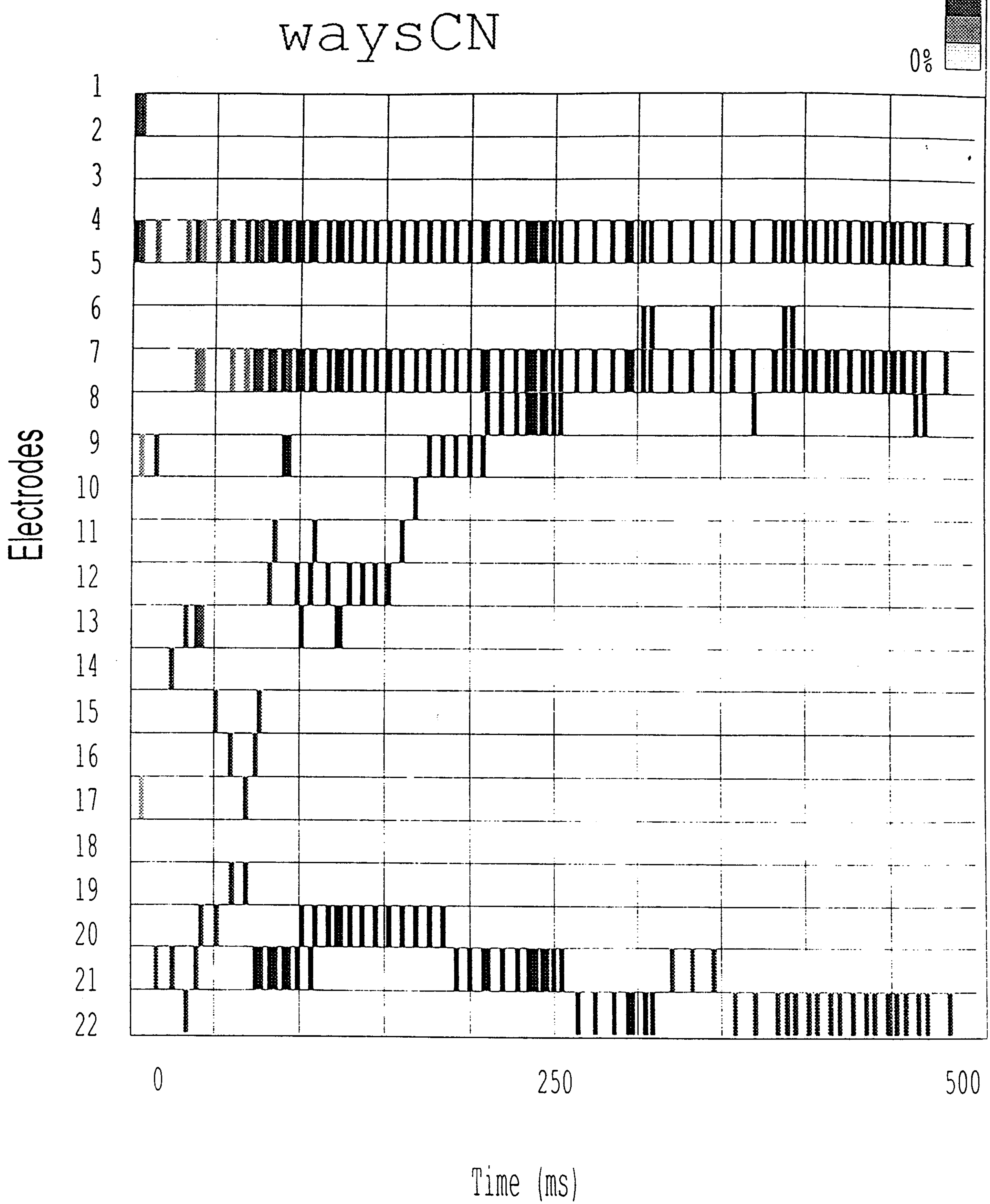

ratCN
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)

Figure 12



WaysLs
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)

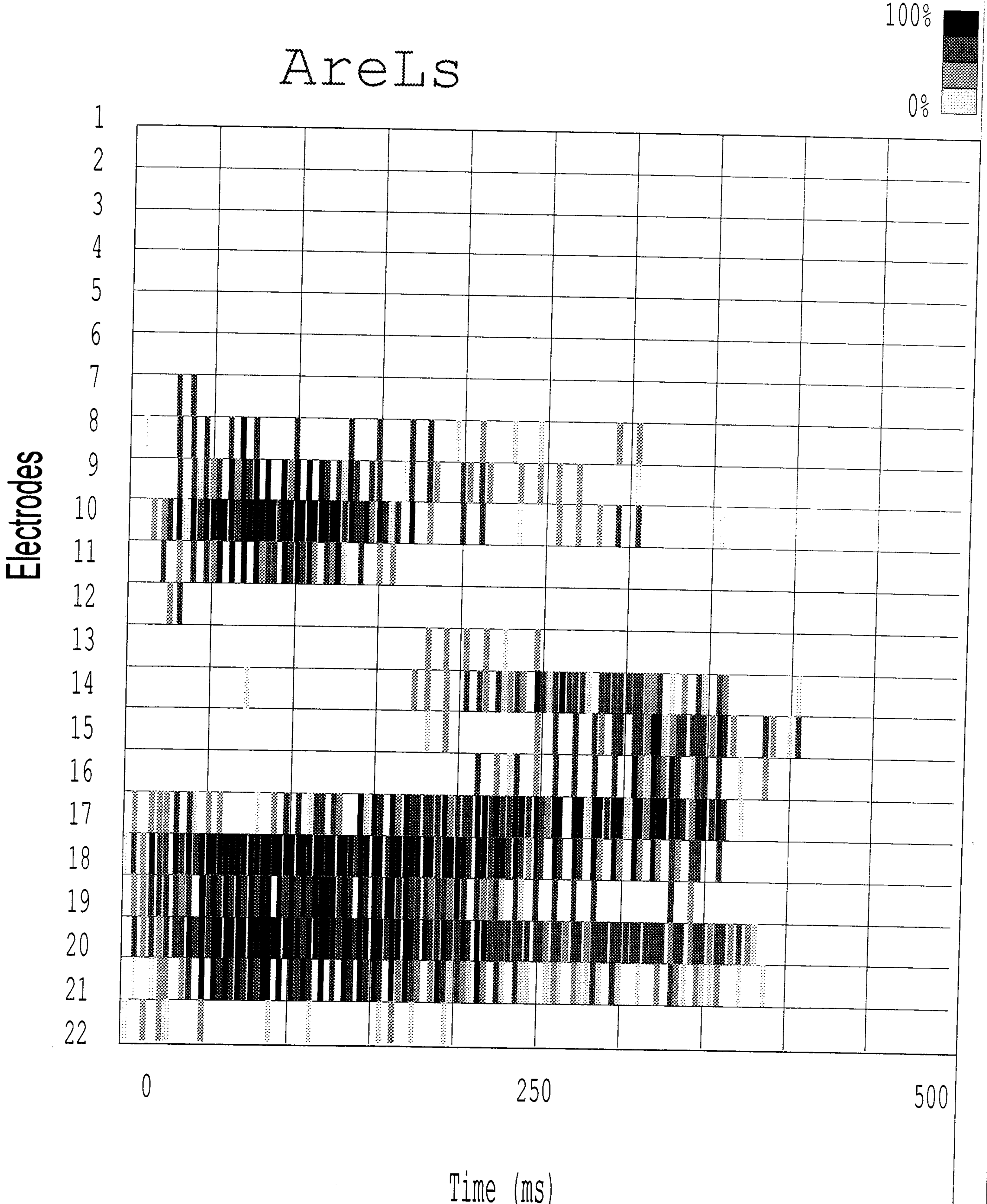
Figure 13


waysCN
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)

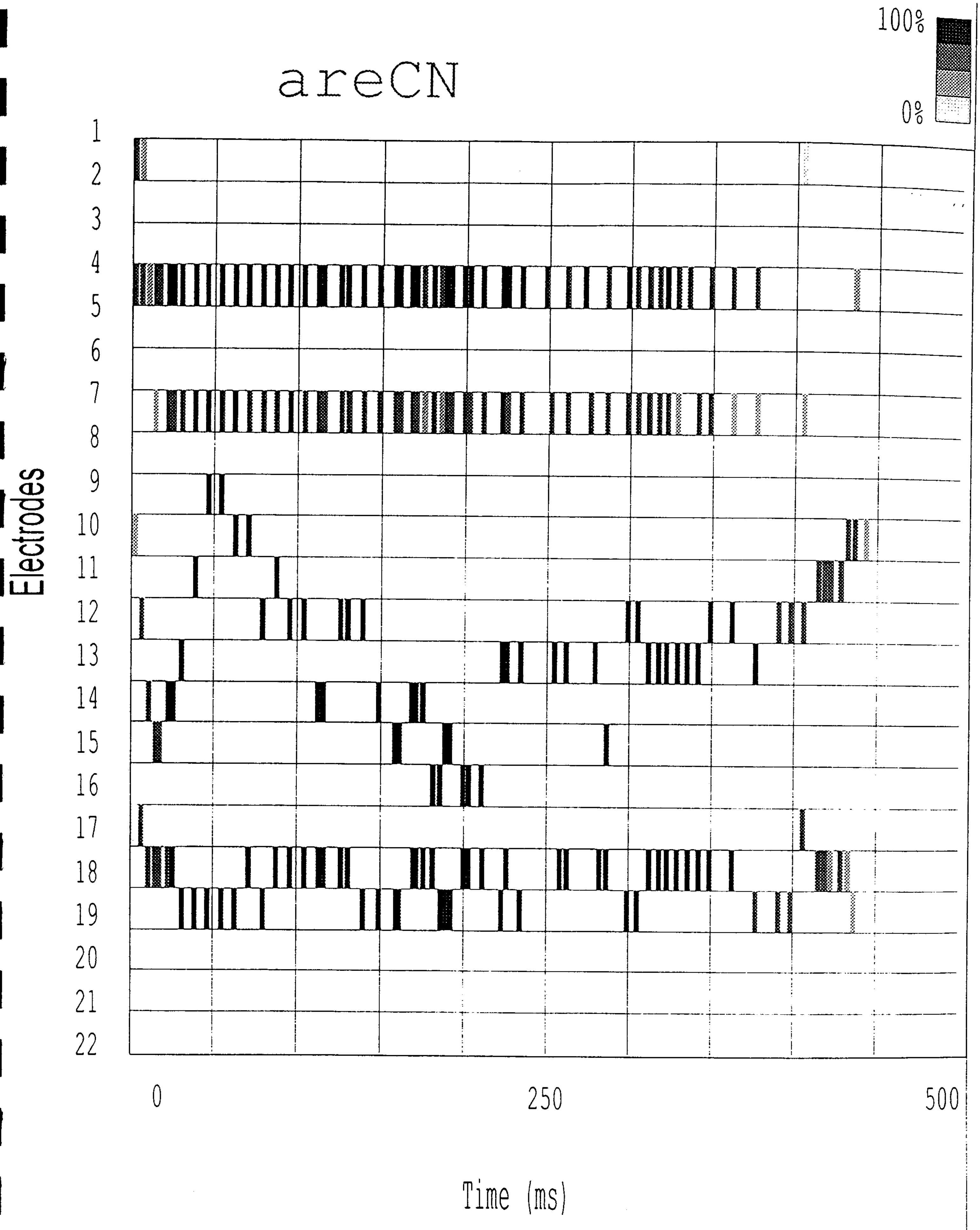
Appendix

sub #	name	group	phonemes	stops	fricative	nasal	glide	high vowels	low vowels	voicing		
1		ha	71	82	90	67	100	86	50	88		
2		ha	55	59	74	17	90	71	67	75		
3		ha	42	77	63	67	60	29	33	74		
4		ha	42	55	68	50	70	71	50	86		
5		ha	39	59	53	33	50	43	83	67		
6		ha	35	73	42	33	90	43	50	81		
7		ha	24	46	26	33	80	86	33	63		
8		ha	17	64	21	17	20	43	33	54		
9		ha	9	46	26	0	20	57	67	42		
10		spc	89	91	84	67	90	100	100	95		
11		spc	43	91	47	0	40	57	67	65		
12		spc	40	59	74	17	80	71	67	70		
13		spc	38	41	47	33	70	57	67	54		
14		spc	37	55	58	33	80	71	83	72		
15		spc	37	46	68	17	80	43	33	63		
16		spc	34	82	42	17	80	43	33	74		
17		spc	32	32	37	17	60	57	33	61		
18		spc	29	46	47	17	40	71	67	65		
19		spc	27	55	47	0	60	43	50	53		
20		spc	23	68	32	0	60	86	17	60		
21		msp	32	59	68	0	50	100	67	58		
22		msp	29	64	63	33	60	43	33	61		
23		msp	28	64	68	0	50	86	17	70		
24		msp	28	46	53	17	50	71	50	56		
25		msp	24	36	58	17	30	71	50	47		
26		msp	16	46	74	17	40	100	17	56		
27		msp	16	18	53	0	10	71	17	39	sd:	words
	means:	ha	37	62	51	35	64	59	52	70	15	14
		spc	39	61	53	20	67	64	56	67	12	15
		msp	25	48	62	12	41	77	36	55	10	5
		diff	14	15	11	23	26	19	20	15		
		F test	1.84	1.70	0.85	3.11	**3.30**	1.88	1.95	2.90		0.88
		p	0.18	0.20	0.44	0.06	**0.05**	0.17	0.16	0.08		0.43
		post-hoc					spc>msp					

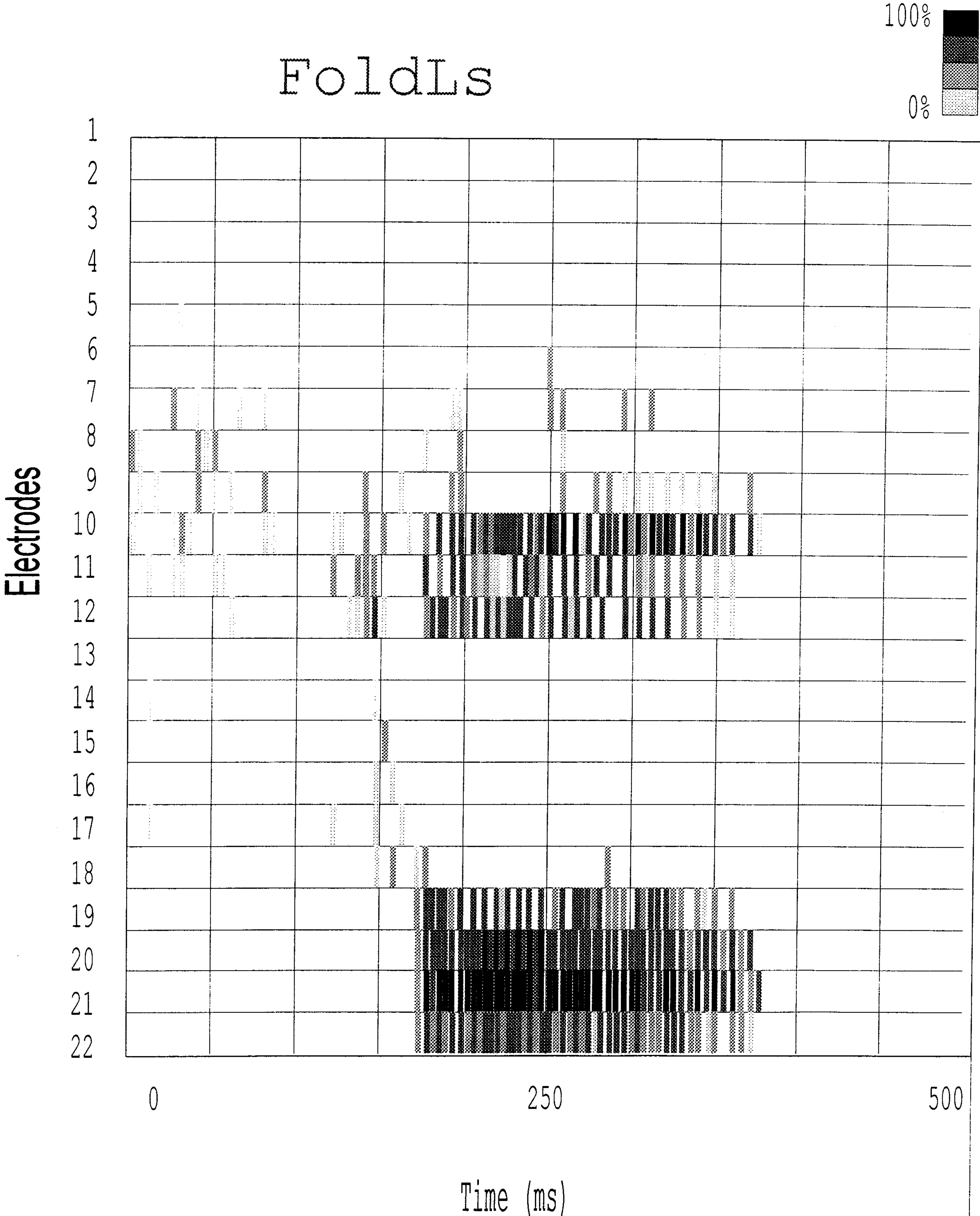
QStall data II, 3/1/96

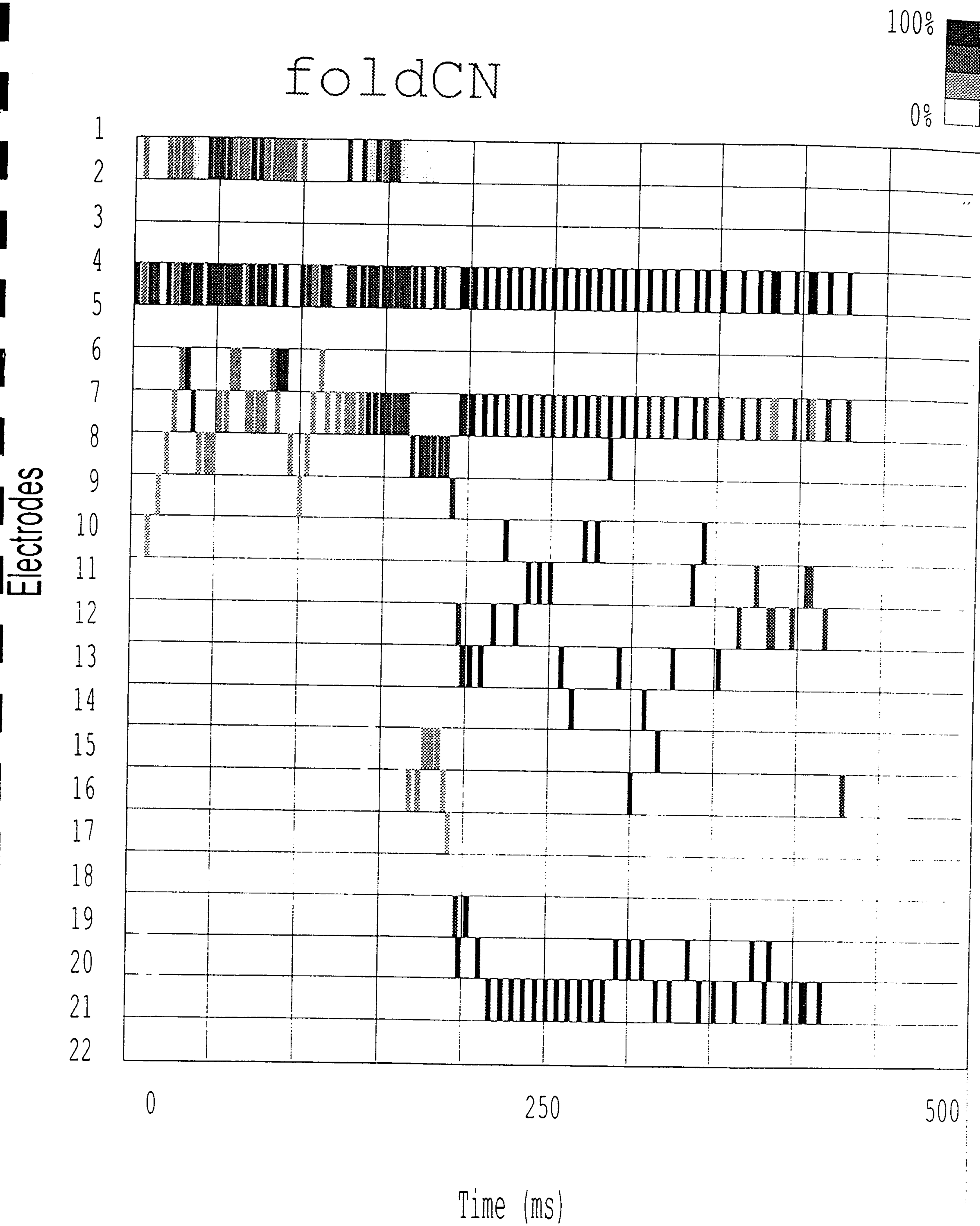


AreLs
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)

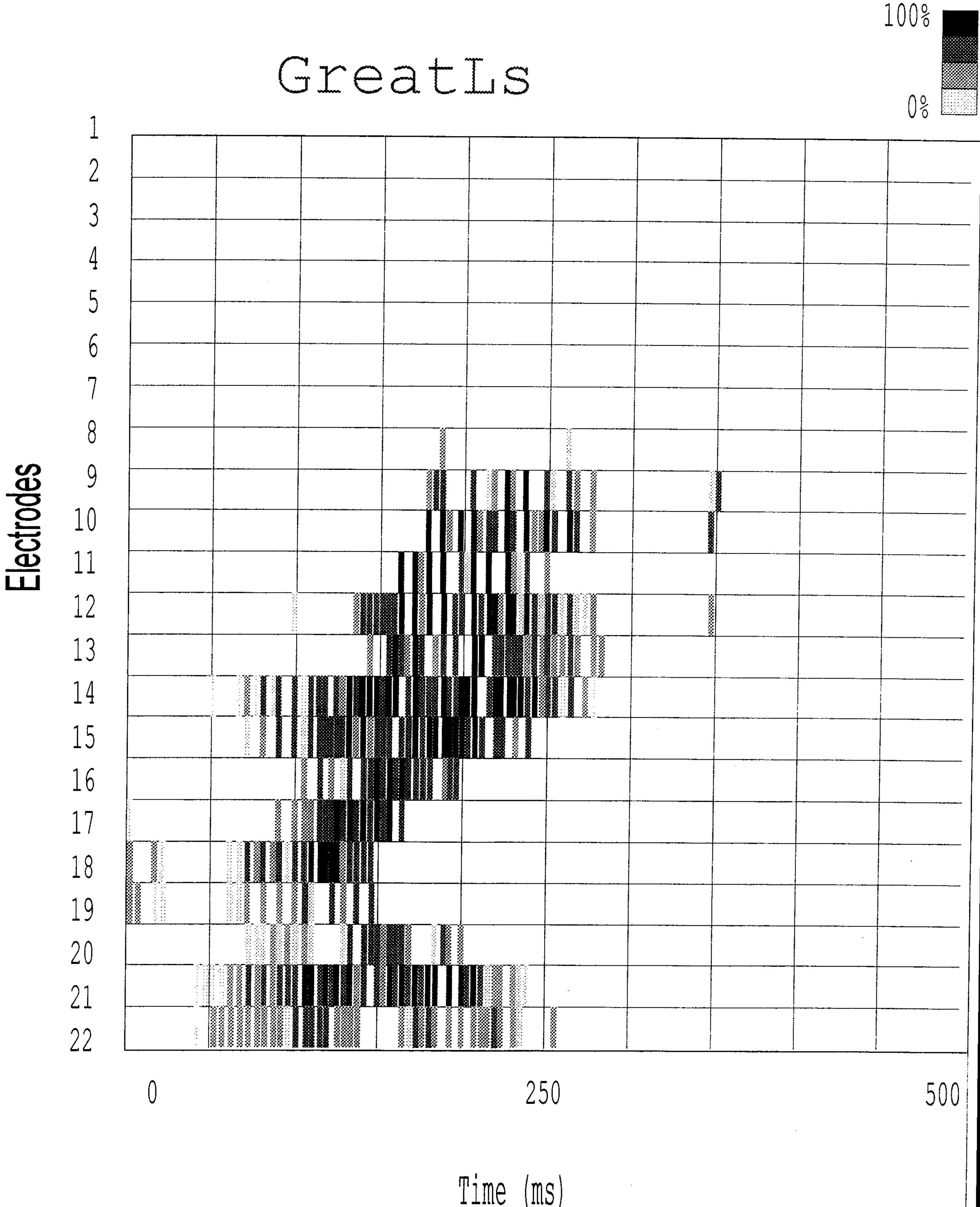


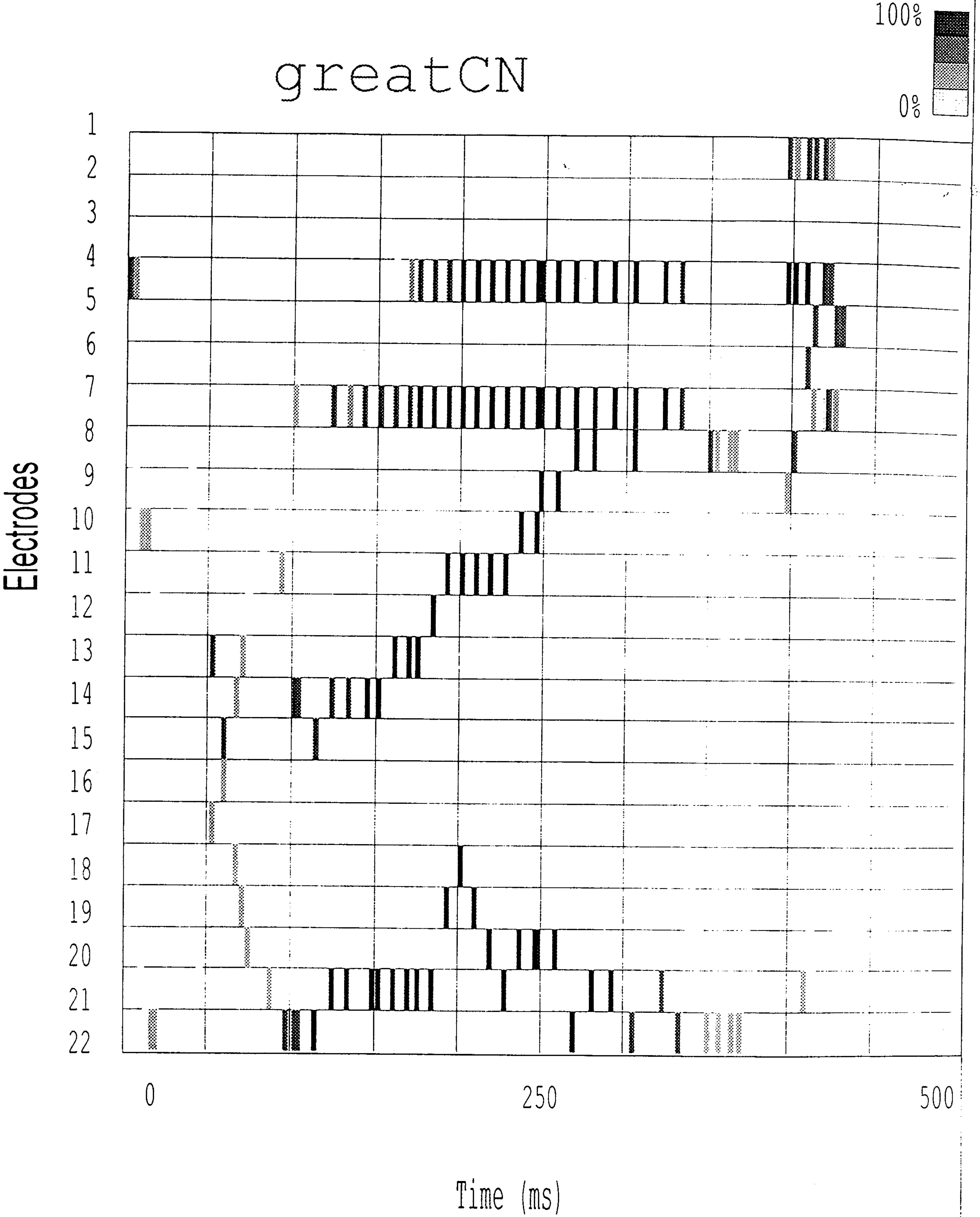
areCN
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)


FoldLs
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)



foldCN
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)


GreatLs
100%
0%
Electrodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
250
500
Time (ms)


greatCN
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Electrodes
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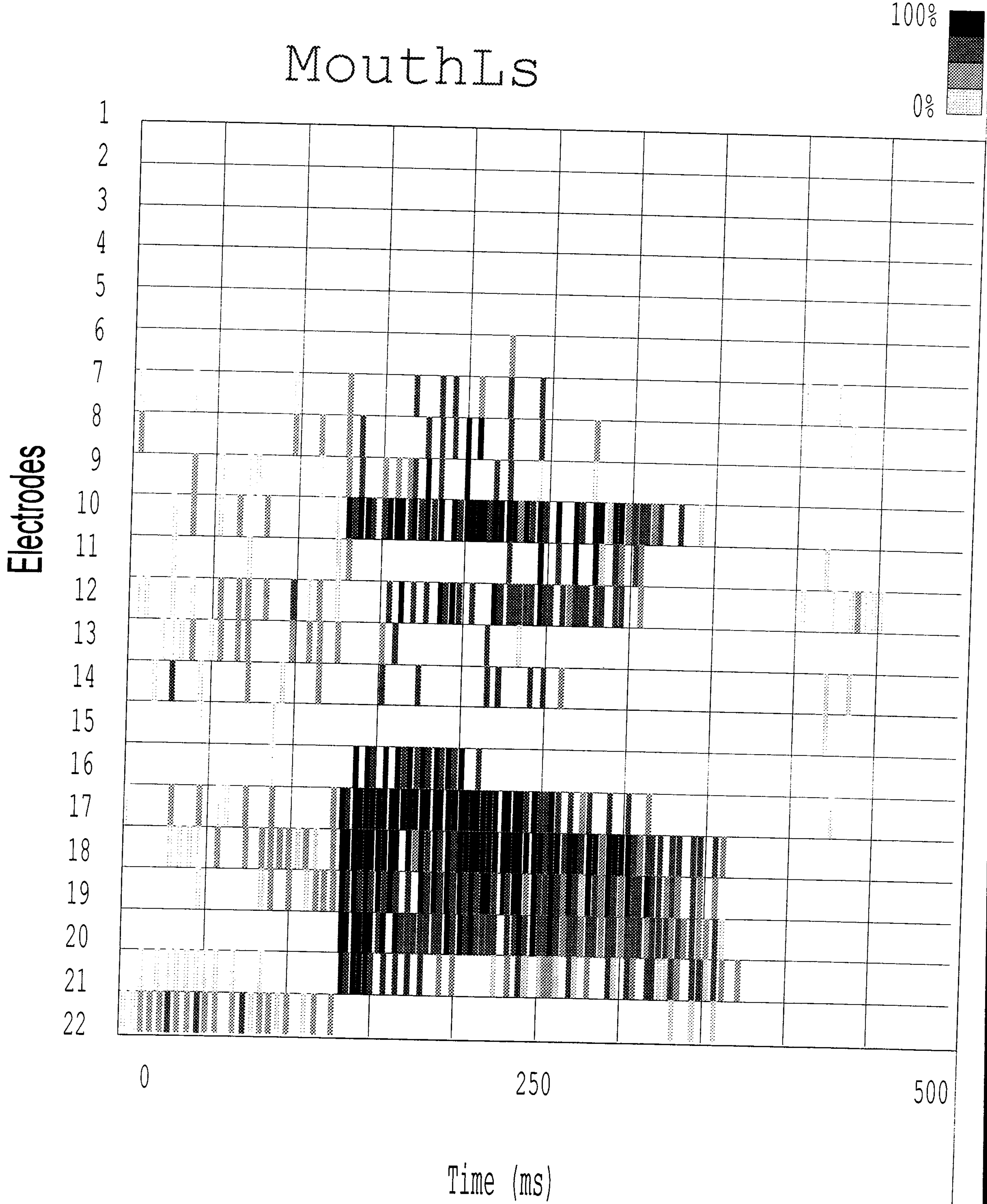
Time (ms)



MouthLs
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Electrodes
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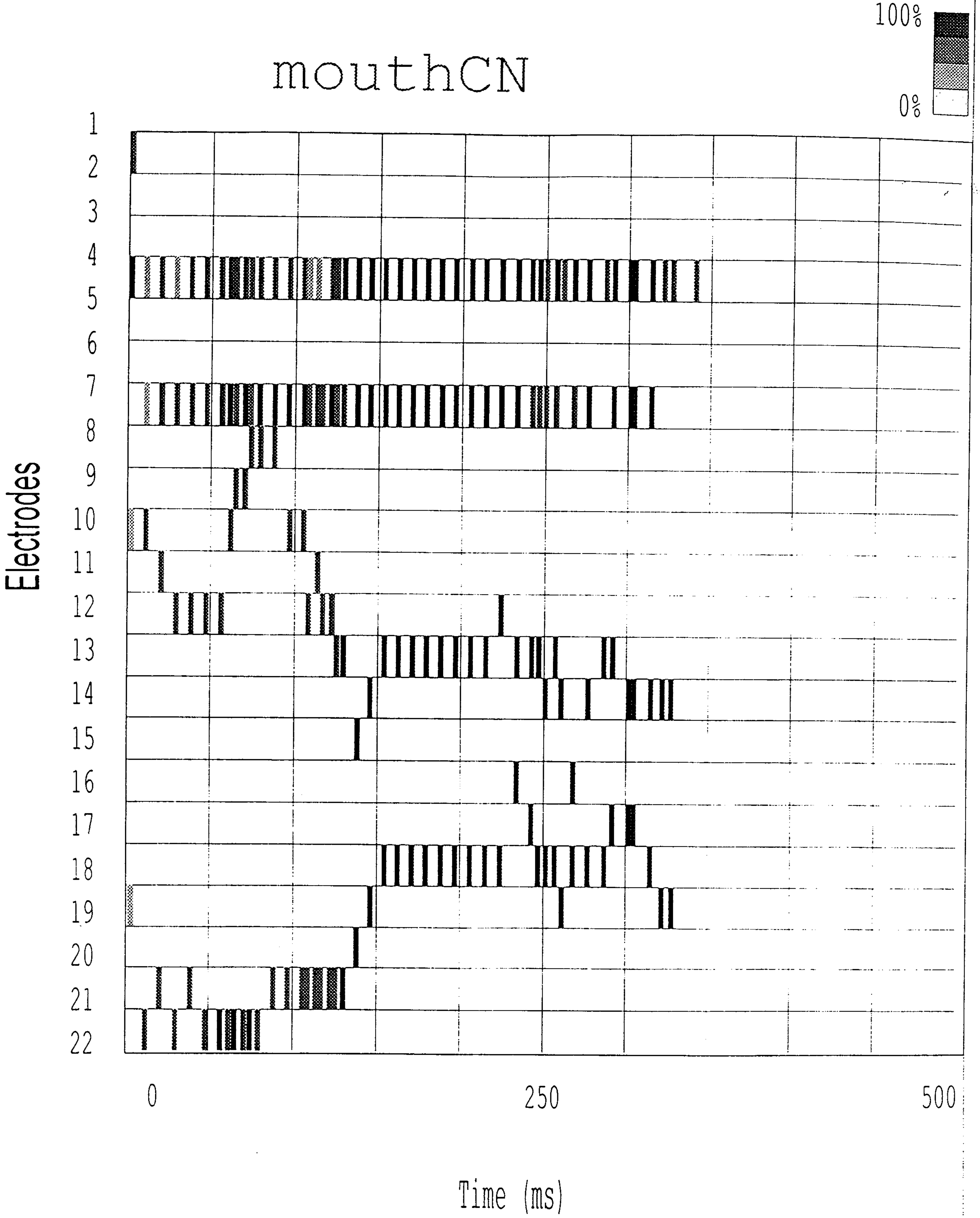
Time (ms)



mouthCN
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Electrodes
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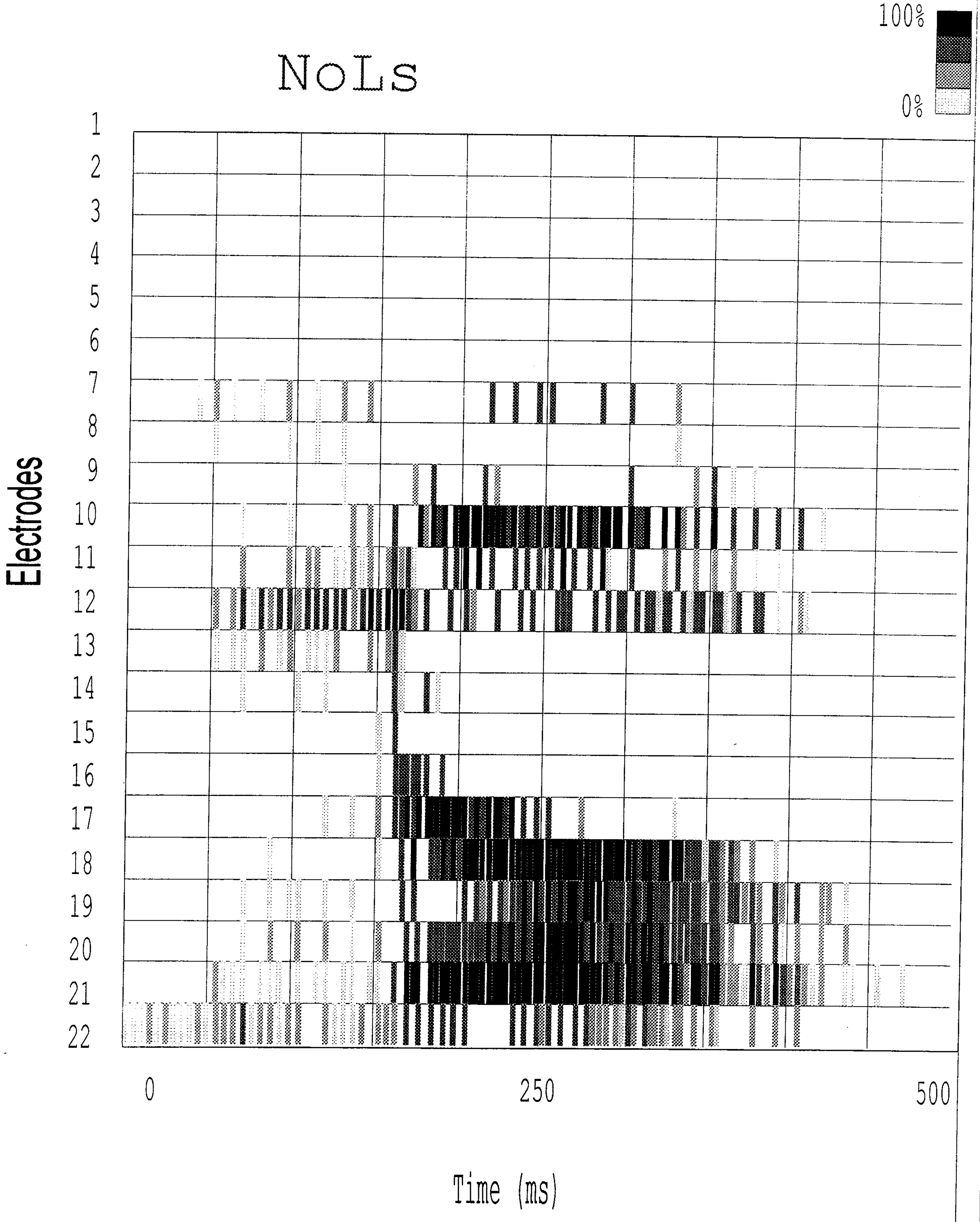
Time (ms)



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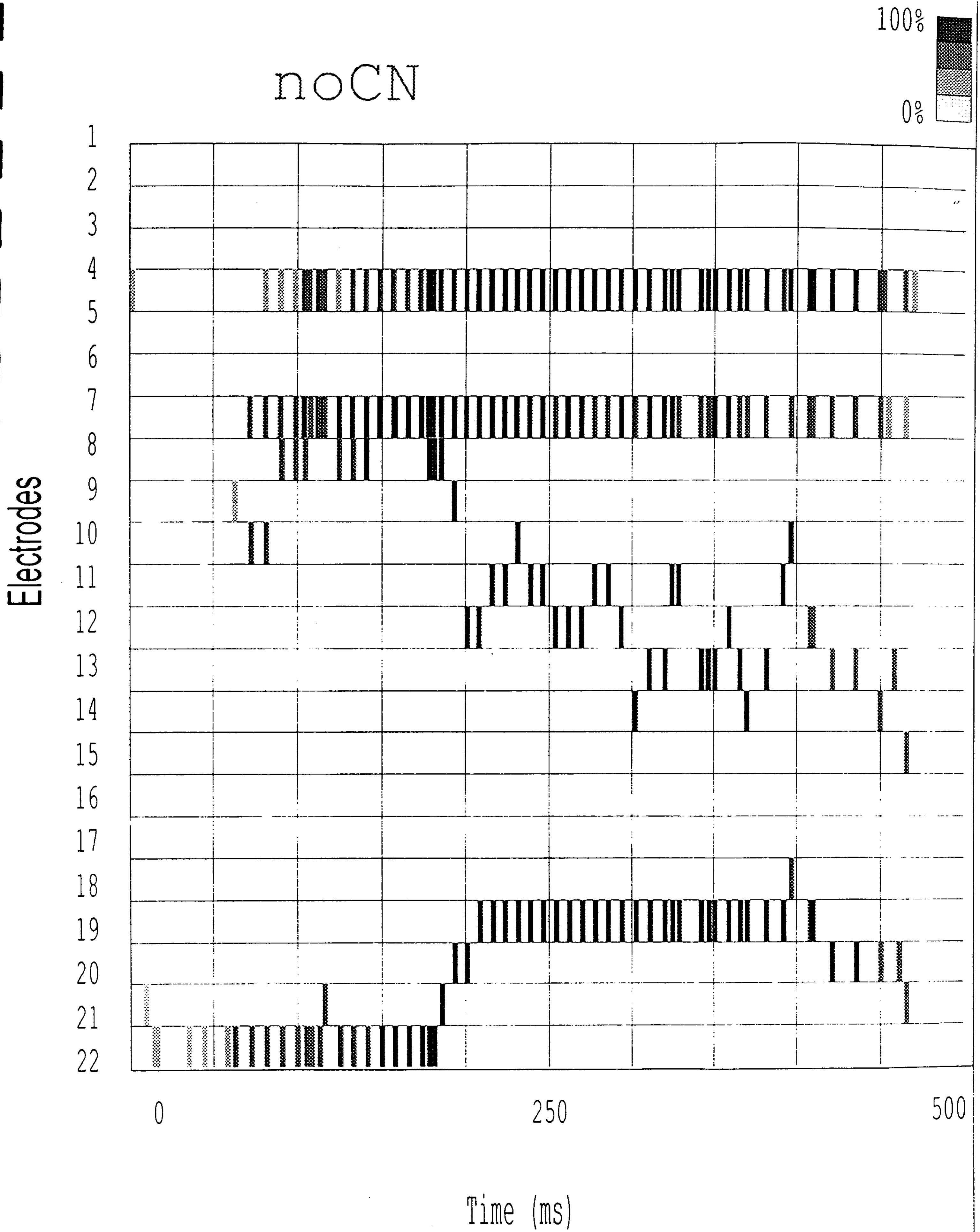
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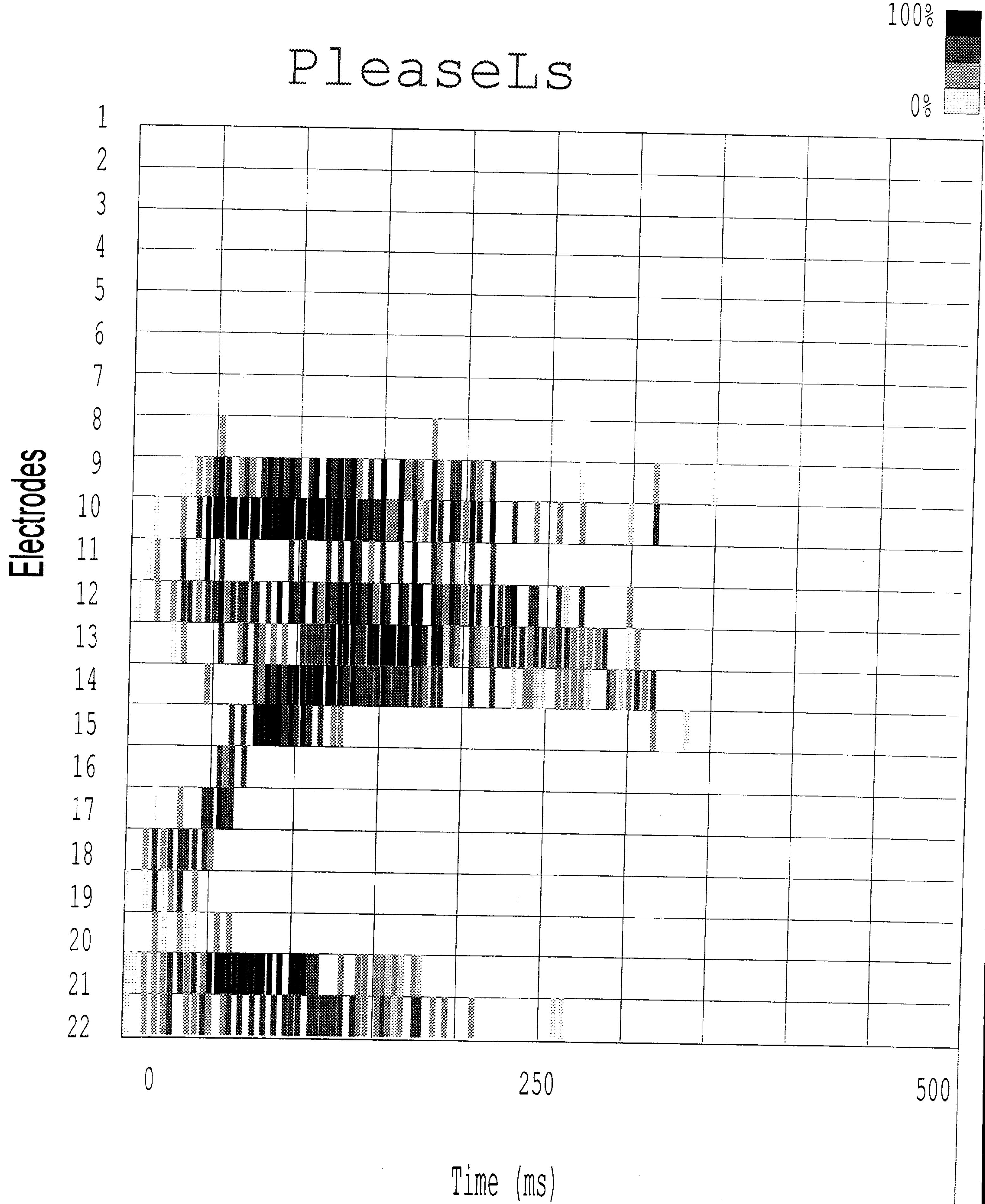
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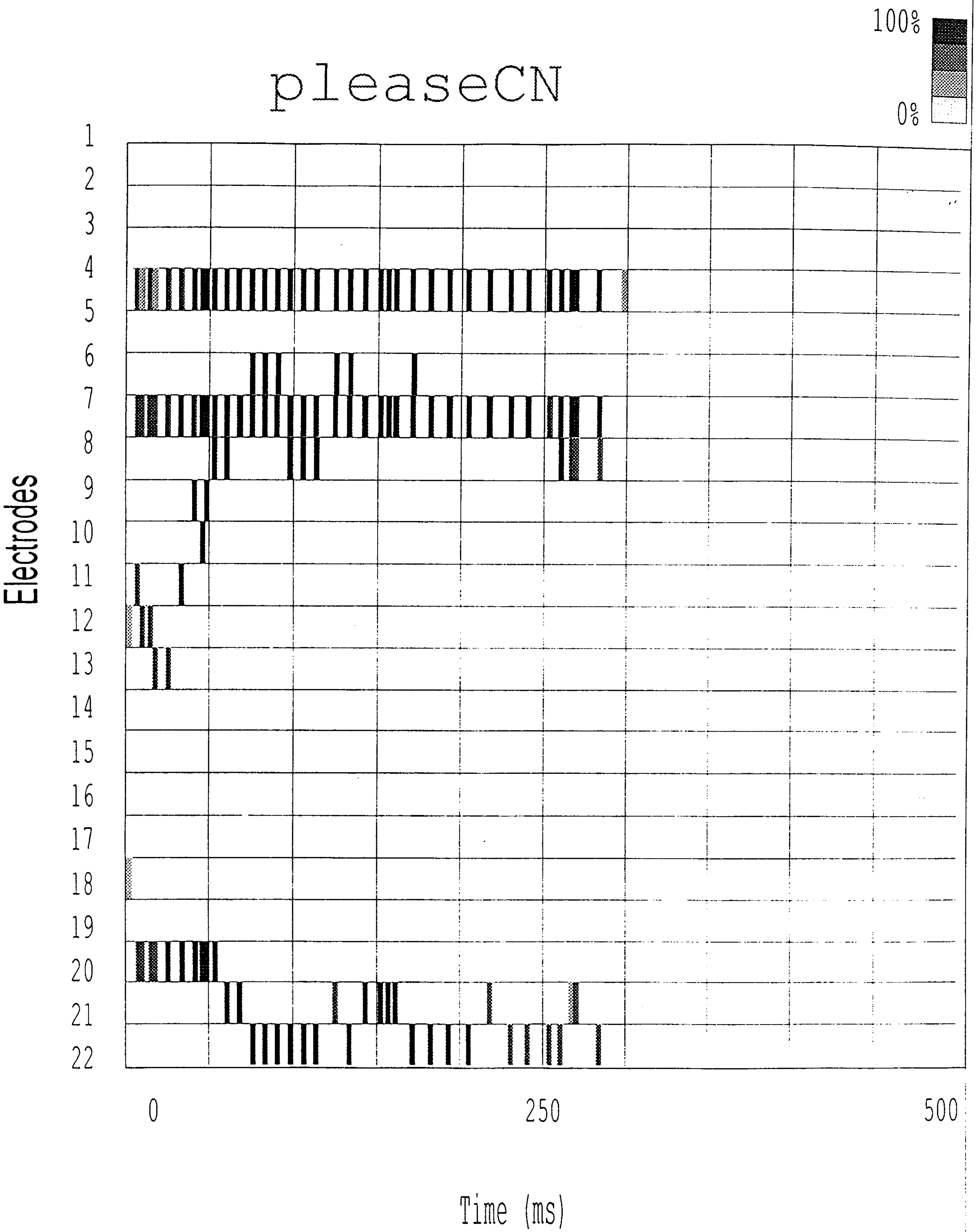
pleaseCN
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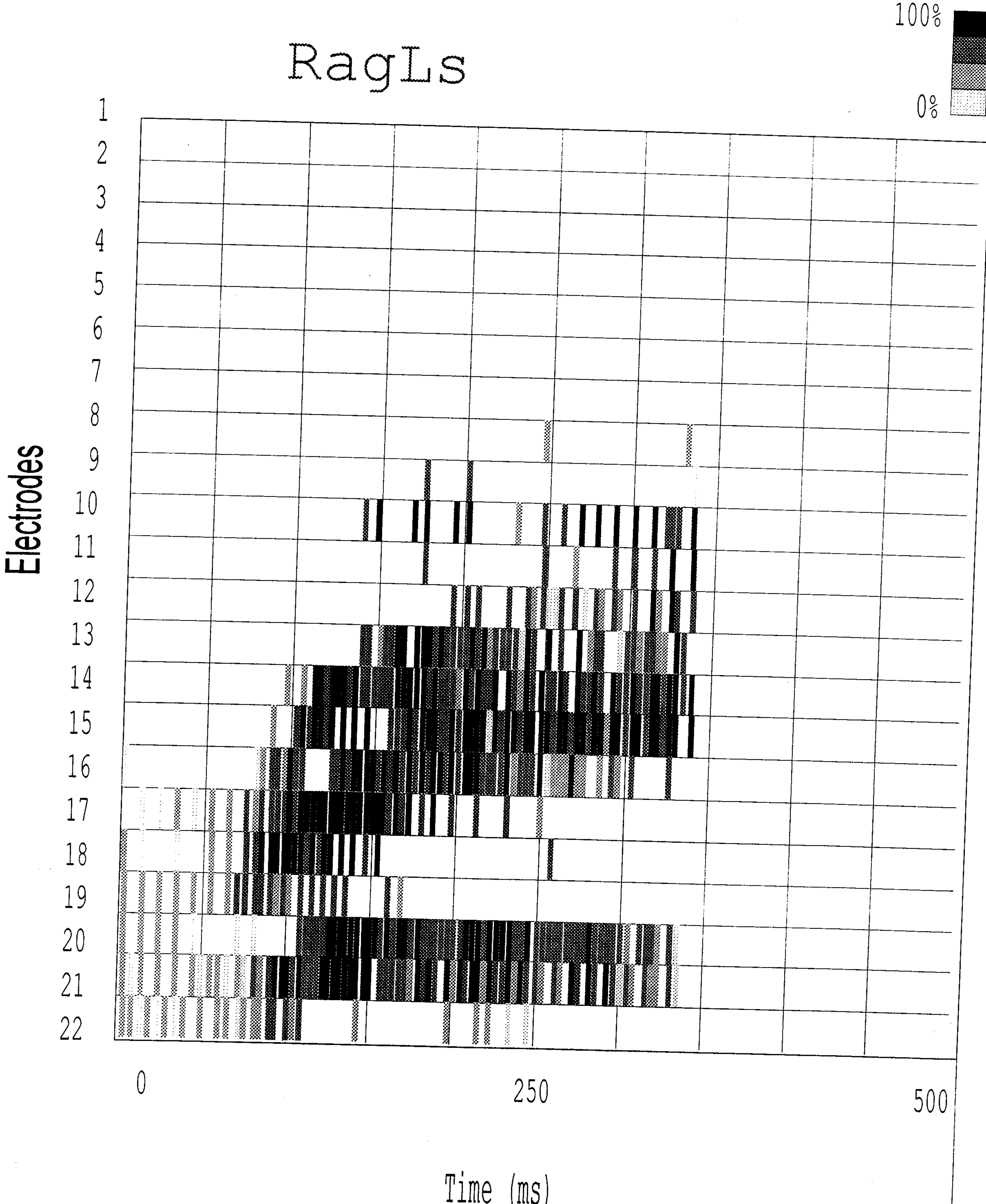

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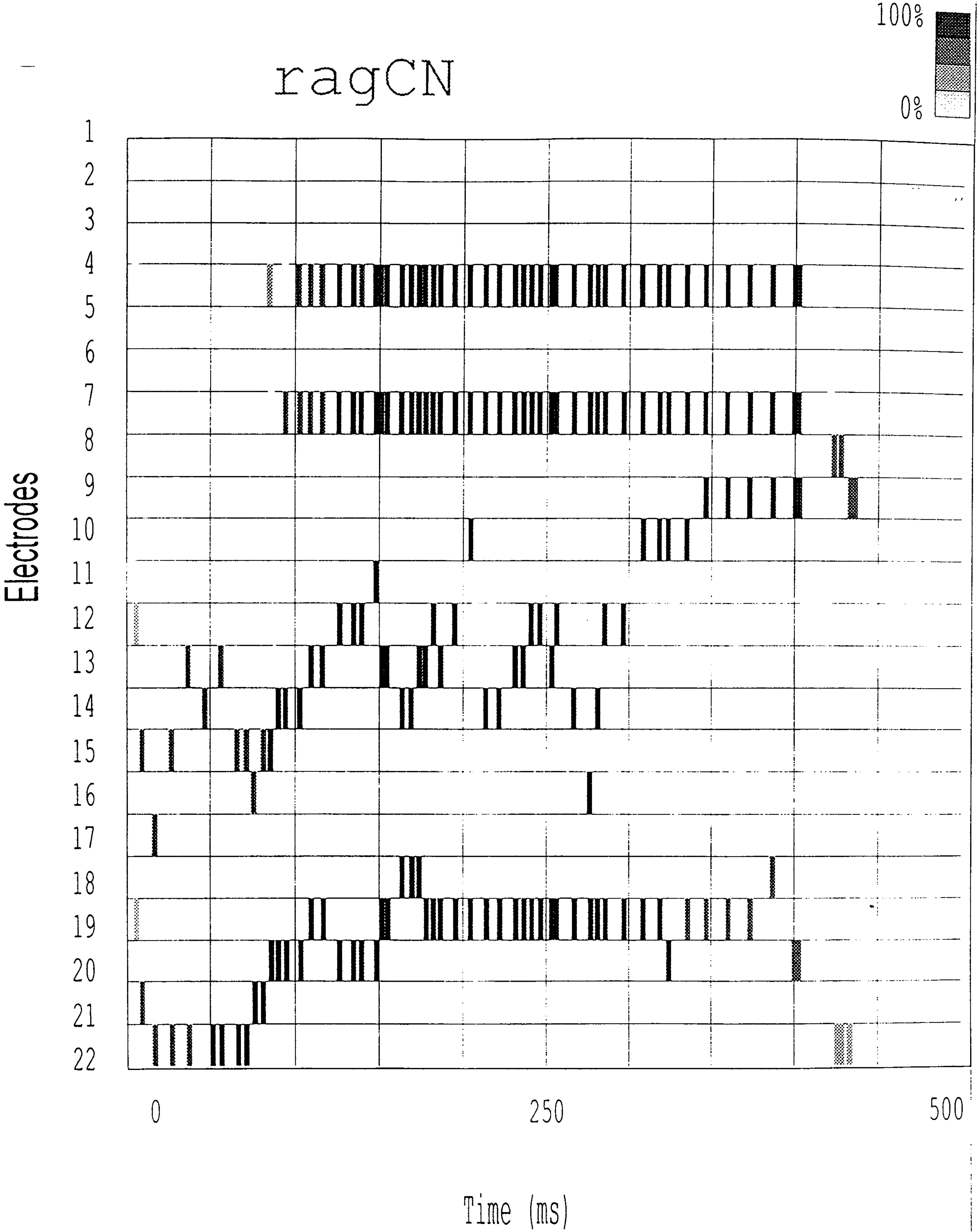

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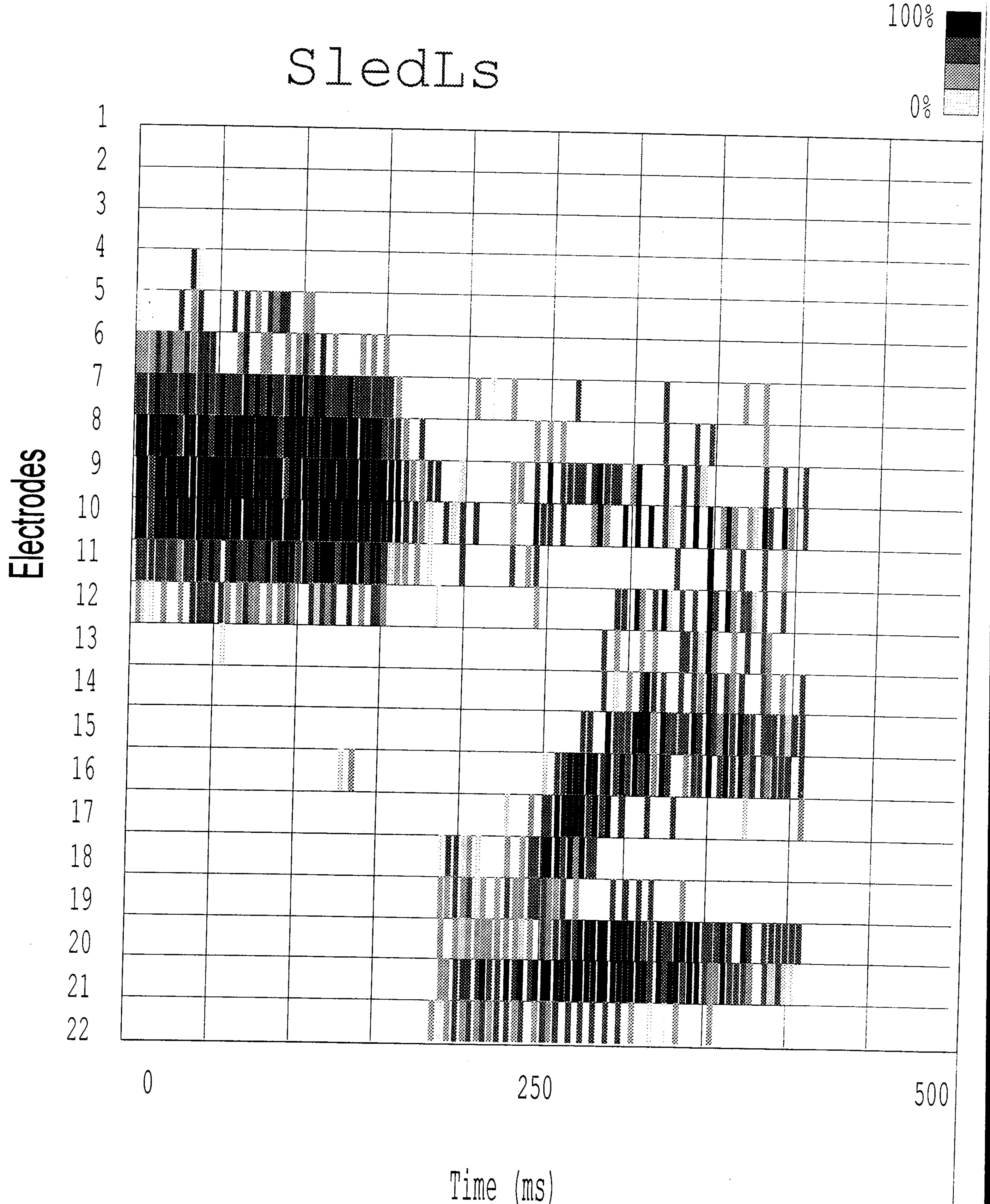
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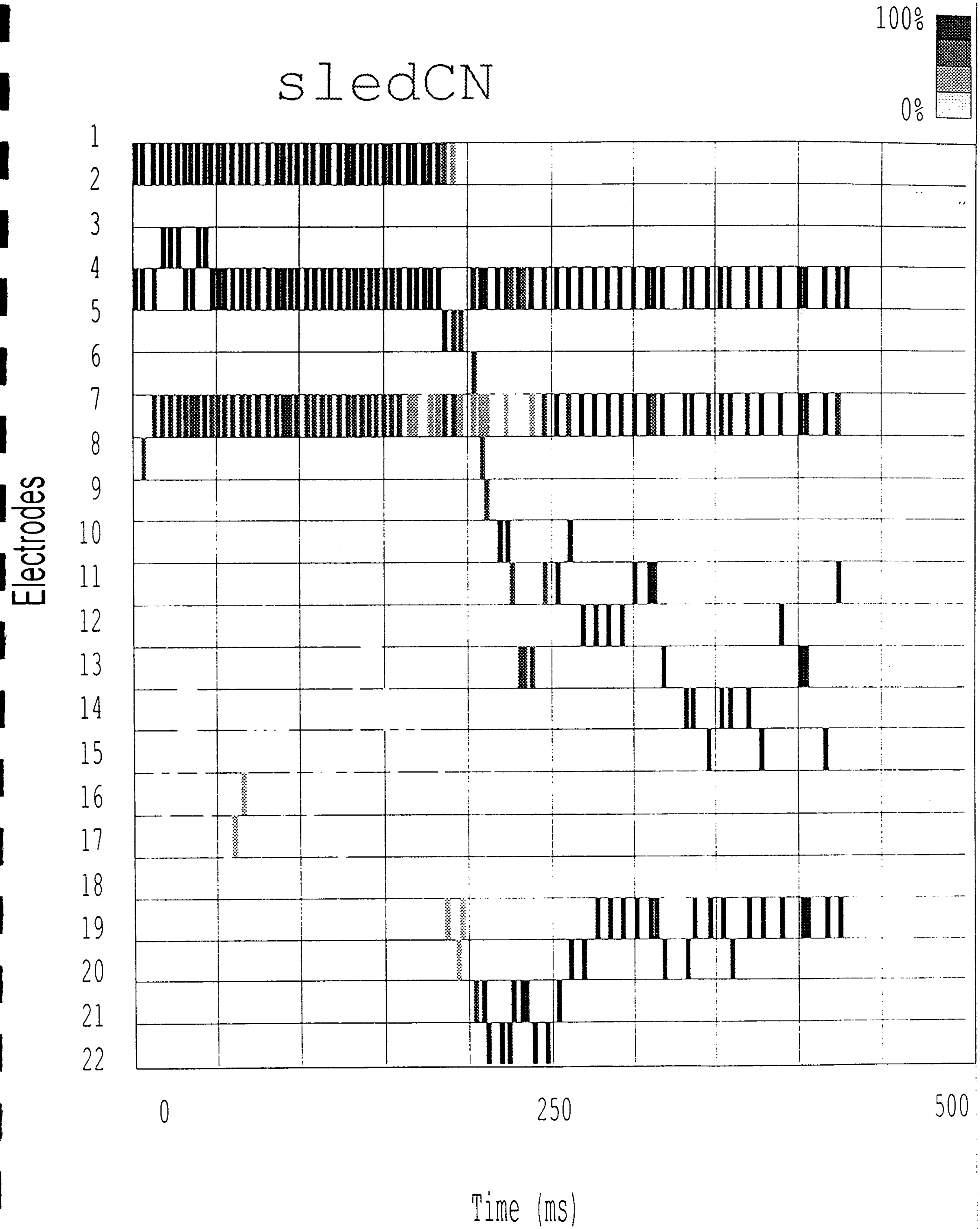

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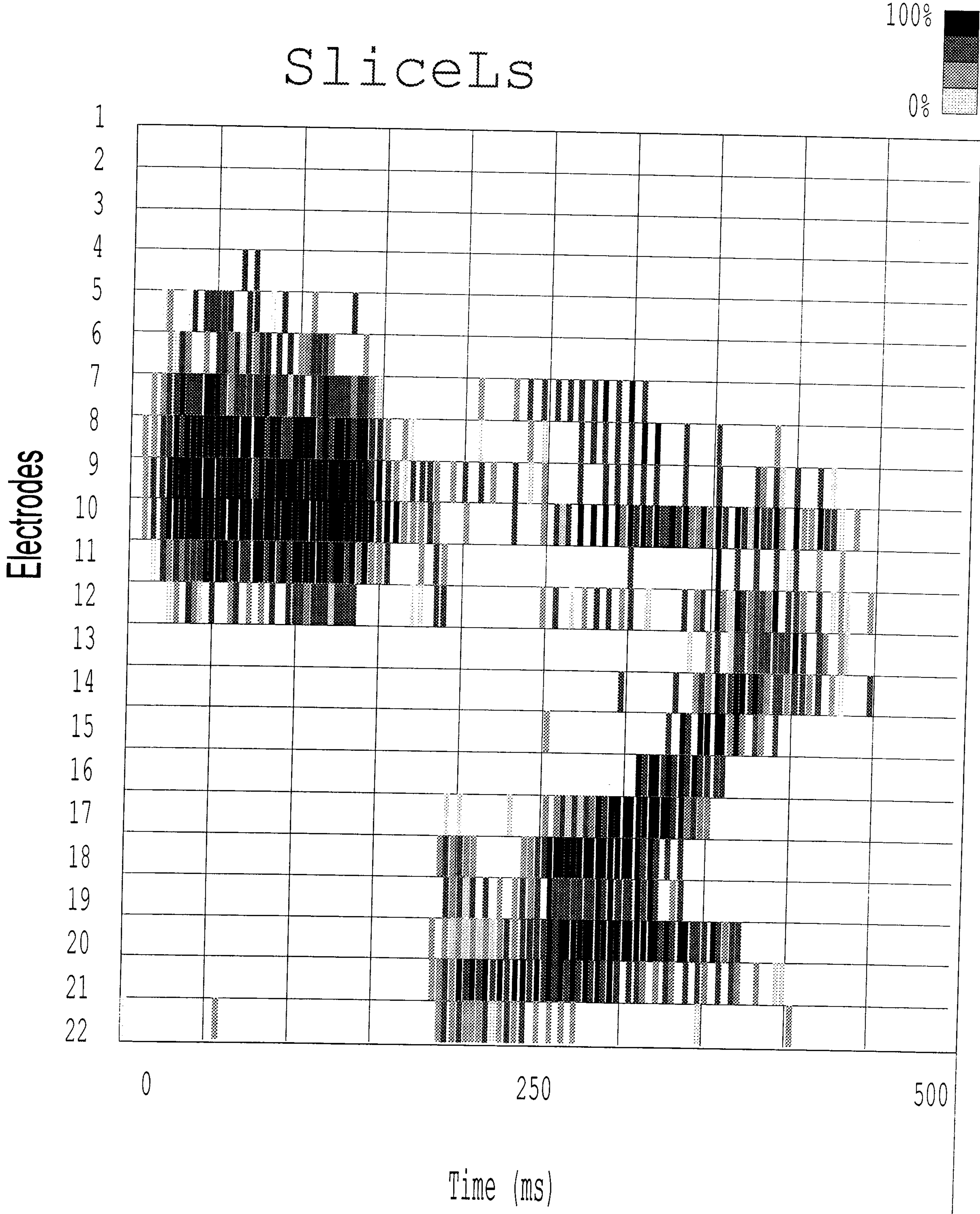
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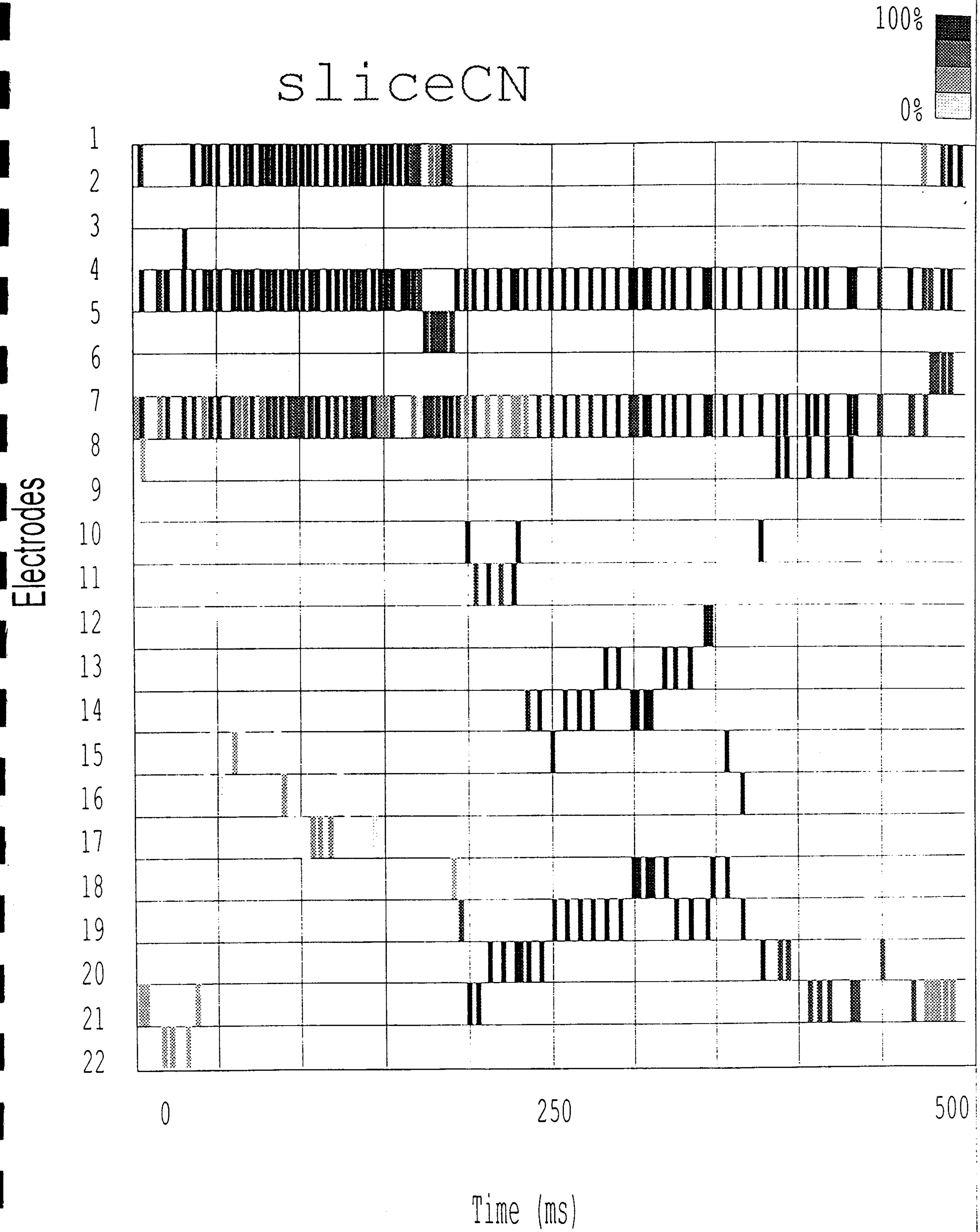
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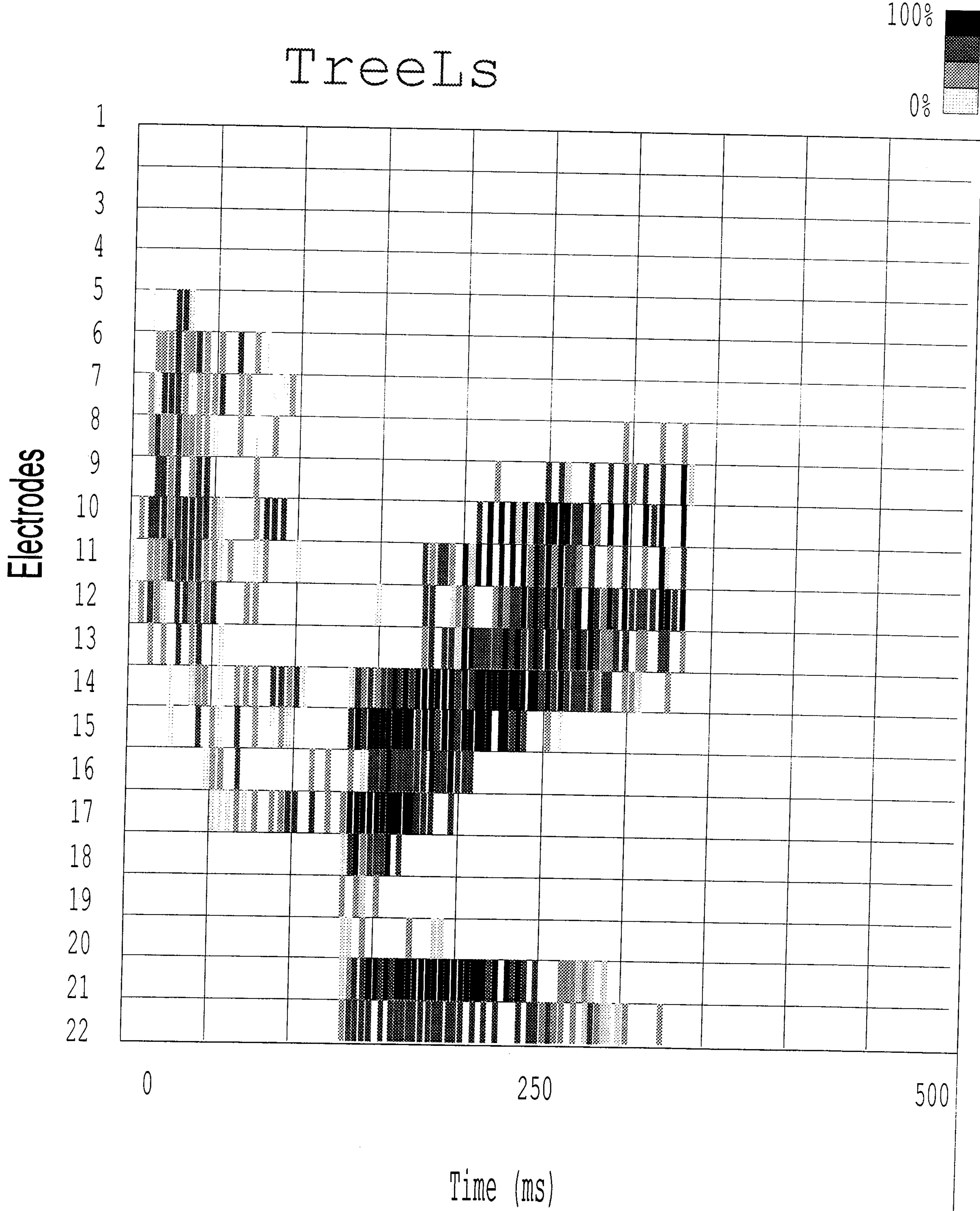
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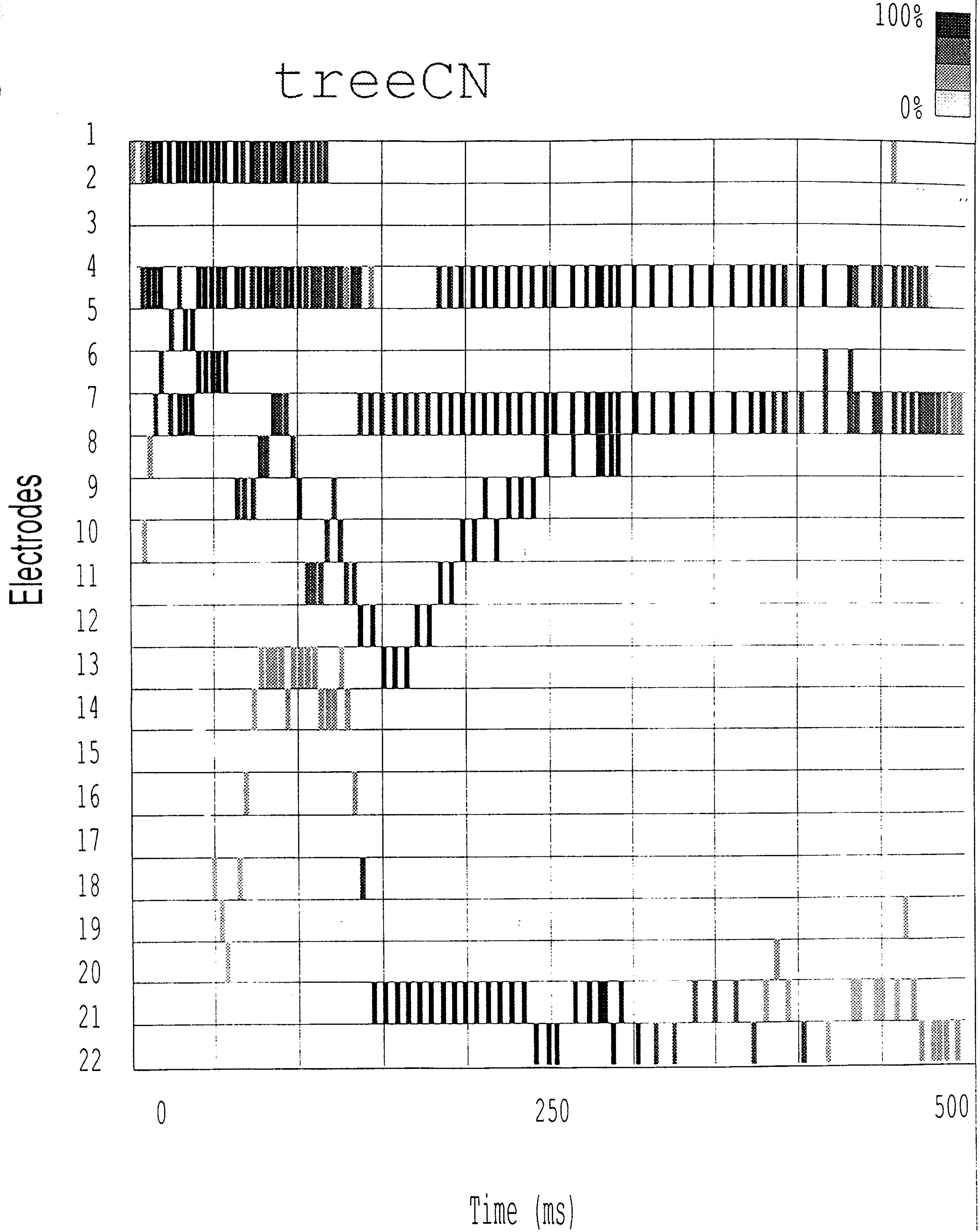
Time (ms)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